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LINC Based Amplifier Architectures for Power Efficient Wireless Transmitters

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ÉCOLE POLYTECHNIQUE DE MONTRÉAL

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Cette thèse intitulée:

LINC Based Amplifier Architectures for Power Efficient Wireless Transmitters

Présentée par: ABDELAAL Mohamed M.

en vue de l'obtention du diplôme de: Philosophiæ Doctor

a été dument acceptée par le jury d'examen constitué de:

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Dedication

I would like to dedicate this work to my late father and my mother, as without their insistence and encouragements I would not had gone in this way and finish my Ph.D.

Also my dedication is due to my wife and my kids for their patience and help through my study for this degree.

Finally I would like to dedicate this work to my country Egypt as without the support I got from the beginning I would not attain what I have today.

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Résumé

De nos jours, les applications sans fil à taux élevé de transfert de données sont de plus en plus répandues. Ces applications nécessitent l'utilisation de systèmes de communication sans fil à haut débit, ayant une bonne efficacité spectrale ainsi qu'une rentabilité optimale en termes de coûts de mise en œuvre et de compatibilité avec les systèmes préexistants. Afin d'explorer ce genre d'application, différentes techniques de modulation de signaux et d'amplification de puissances sont actuellement en cours d'exploration. L'objectif est de répondre au mieux aux exigences accrues des consommateurs pour la transmission de données à très haut débit (notamment les données vidéo) tout en permettant aux opérateurs des réseaux mobiles de réduire au maximum les coûts de maintien et de déploiement de ces réseaux. Cette tendance a accéléré l'adoption de nouveaux standards de quatrième génération (4G) dont le potentiel se manifeste à plus d'un titre.

En premier lieu, la technologie 4G promet un accès sans fil rapide et à large bande. Par ailleurs, une fois les circuits intégrés sont assez bon marché, la nouvelle technologie ne sera plus utilisée seulement dans les appareils mobiles et les ordinateurs portables, mais aussi dans certains périphériques tels que les appareils photo numériques et les compteurs électriques. C'est dans ce contexte que se situent les travaux de cette thèse qui vise à développer de nouvelles techniques d'amplification de puissance RF pour les nouveaux systèmes sans fil de quatrième génération. En raison de la quantité de puissance considérable qui peut être dissipée lors de l'amplification, l'efficacité des amplificateurs de puissance s'avère un des principaux facteurs affectant la performance globale du système. Les techniques existantes pour améliorer l'efficacité de l'amplificateur causent la dégradation de la linéarité, ce qui est intolérable pour les nouveaux systèmes de communication sans fil employant des techniques de modulation avancées. En effet, l'inconvénient principal d'une modulation complexe d'un signal, tel que la modulation OFDM (Orthogonal Frequency Division Multiplexing), est que signal

de crête peut s'élever à N fois la puissance moyenne (N peut être supérieur à 10)|, ce qui force l'amplificateur à travailler instantanément dans la région non-linéaire, causant ainsi des distorsions d'intermodulation et l'augmentation des taux d'erreur binaire BER (Bit Error Rate), ou encore à travailler avec un grand recul pour avoir une meilleure linéarité mais au prix d'une perte d'efficacité énergétique. Afin de maintenir un compromis entre efficacité et linéarité, une technique d'amplification est proposée. Il s'agit d'une solution au niveau système visant à offrir un rendement élevé tout en préservant la linéarité du signal.

Dans ce projet de recherche, l'étude des nouvelles architectures d'émetteur RF a été effectuée tout en mettant l'accent sur des topologies pouvant répondre aux exigences actuelles en termes de linéarité et d'efficacité. Afin de résoudre le problème de la dégradation de l'efficacité de l'architecture LINC (LInear amplification with Nonlinear Components) conventionnelle causée par les pertes au niveau du combineur, une nouvelle solution de LINC modifiée au niveau système est proposée. Au lieu d'être combinés au niveau de l'émetteur, les signaux des deux branches sont amplifiés, transmis et ensuite combinés au niveau du récepteur. Par conséquent, l'efficacité de tout le système s'améliore tout en garantissant la linéarité des signaux modulés. La nouvelle architecture proposée possède l'avantage d'utiliser deux amplificateurs non linéaires opérant à saturation dans leurs régions de haute efficacité énergétique. De plus, cette architecture ajoute une flexibilité au niveau du système pour compenser les distorsions du signal causées par le canal et les déséquilibres des branches LINC.

Les principales contributions de cette thèse sont énumérées comme suit:

Tout d'abord, la séparation du signal de l'amplificateur LINC ainsi que le filtrage des signaux des branches sont réalisés à l'aide d'une unité d'implantation DSP (Digital Signal Processing). Grâce à cette implantation, la performance de tout le système est améliorée non seulement en termes d'efficacité de puissance mais aussi en termes

d'ACPR (Adjacent Channel Power Ratio) et de déséquilibres entre les branches du LINC. En outre, deux nouvelles architectures d'amplification LINC au niveau système (2X1 et 2X2) pour les systèmes de communication sans fil sont présentées. Les résultats du la simulation montrent une amélioration de l'efficacité et une bonne immunité aux déséquilibres des branches des signaux tout en gardant un niveau de linéarité acceptable.

Abstract

Nowadays, high speed and high data rates based wireless applications are largely widespread. These applications require wireless communication systems with broadband and high spectral efficiency in addition to cost and compatibility effectiveness. Different modulation and power amplification techniques are being studied and explored for these applications as the wireless communication systems are continuously in development, as the need for cost-effective, spectrum-efficient, ubiquitous, always-on and interoperable wireless systems.

The increasing consumer demand for higher speed mobile data services and the mobile network operators need for ways to cut costs accelerated by the adoption of the new futuristic 4G standard. The 4G technologies promise a wireless access which is fast and ubiquitous broadband. Once the radio IC chips are cheap enough, the new technology will not just be used in handsets and laptops, but also in devices such as digital cameras and electricity meters, which are unconnected today.

Based on the beforehand discussion this research project is aimed at developing new efficient RF power amplifying techniques for these emerging wireless systems. The efficiency of power amplifier is one of the most critical factors affecting the overall system performance due to the power dissipation in the amplification stage. The existing techniques used to improve amplifier efficiency result in a loss of linearity, which is unacceptable for the new wireless communication systems employing advanced spectrally-efficient modulation techniques. The new complex modulated signals, like OFDM, main disadvantage is that the signal peak may rise up to N times (N can be higher than 10) the average power, which will force the amplifier to work in the nonlinear region, causing inter-modulation distortions and an increase in Bit Error Rate (BER) or work with a large back up to keep the linearity, but in this case the power efficiency degrades considerably.

To remedy this compromise between efficiency and linearity, an efficient amplification technique is proposed in this thesis. It is based on a system-level solution to provide high efficiency while maintaining linearity of the signal.

In this research project a study for new transmitter architectures with emphasis on topologies that can meet today's linearity and high efficiency requirements was carried out. Due to the conventional LINC efficiency degradation problems owing to the combiner losses, a new system level modified LINC solution is proposed. This new solution introduces a new topology intended for efficiency of the power amplification front end in wireless communication transmitters. Instead of combining them at the transmitter the two RF amplified branch signals are transmitted and then combined at the receiver. Accordingly, the LINC based transmitter efficiency is improved, and the overall system power efficiency is enhanced, while the linearity of the modulated signals is maintained. This new architecture has the advantage of using two nonlinear amplifiers working in saturation in their high efficiency operation region, and also adds flexibility at the system level to compensate for the signal distortions due to the channel and LINC branches imbalances.

The main contributions of this thesis are listed as follows:

An addition of an extra filtering step in the processing, taking place in the signal separation unit of the LINC transmitter, results in an improved LINC amplifier system performance from the perspective of linearity and robustness to branch mismatches in terms of gain and phase unbalance.

Furthermore, two novel system level topologies 2X1 and 2X2 LINC amplification solutions for the wireless communication systems are also introduced. These two LINC new architectures are intended to replace the conventional LINC transmitter to reduce degradation of the average efficiency when high peak to average signal is transmitted.

Simulation results show improved efficiency and immunity to branch signals imbalance, while maintaining the required linearity and quality of signal.

Condensé en Français

Introduction

Les systèmes de communication sans fil sont devenus les plus importants moyens de communication. En raison de la forte demande sur des systèmes de communication capables de fournir une connectivité plus facile avec des taux élevés de transfert de données, l'usage de tels systèmes a considérablement augmenté au cours de la dernière décennie. En outre, l'accent s'est déplacé vers des services numériques sans fil permettant de fournir une grande variété d'applications outre que les services généraux de téléphonie vocale fixe. Cette tendance augmente la nécessité de développer des nouveaux systèmes très fiables à capacité élevée. Ceci a stimulé plus de travaux de recherche qui visent à développer d'avantage des services intégrés, fournissant des débits plus élevés ainsi qu'une interface plus universelle pour des applications multistandards.

Cependant, le problème de ces systèmes est qu'ils opèrent dans la bande des fréquences radio (bande RF). Ceci nécessite une attention particulière lors de la conception des différents blocs, notamment le bloc d'amplification de puissance. L'efficacité des amplificateurs de puissance RF est l'un des principaux facteurs affectant la dissipation de puissance dans l'ensemble du système. Ces amplificateurs sont conçus pour fournir un maximum d'efficacité à un seul niveau de puissance situé généralement près de la saturation. Lorsque le point d'opération est reculé (backed off), le rendement se dégrade fortement et la dissipation de la chaleur augmente. Ce problème est inévitable si l'amplitude de l'enveloppe RF varie entre les valeurs minimale et maximale. La plupart des approches visant à améliorer l'efficacité de l'amplificateur causent une perte en linéarité ce qui est intolérable pour les systèmes de communication avancés employant des techniques de modulation visant à améliorer l'efficacité spectrale. En outre, les crêtes des signaux utilisant ces types de modulations complexes, tel que l'OFDM (Orthogonal Frequency Division Multiplexing), peut atteindre plus que dix fois la puissance moyenne, ce qui force l'amplificateur au niveau de l'émetteur à opérer dans la région non-linéaire, causant des distorsions d'intermodulation (i.e. dégradation de la linéarité) et l'augmentation du taux d'erreur binaire BER (Bit Error Rate). Par ailleurs, si l'amplificateur de puissance est exploité en recule (back-off) pour assurer la linéarité du signal, l'efficacité de puissance du système entier est réduite. Ce compromis est illustré graphiquement dans la figure 1.

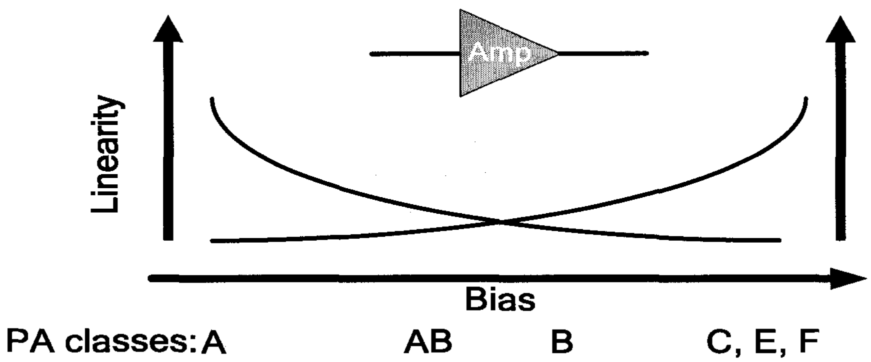

Figure 1: Linéarité et efficacité des différentes classes d'opération des PA.

Différents paramètres sont utilisés pour évaluer les performances des systèmes numériques de communication sans fil. Ces mesures de performance peuvent être généralement divisées en deux grandes catégories, celles mesurant l'efficacité et celles mesurant la linéarité. L'efficacité est mesurée au niveau de l'amplificateur de puissance (PA) et de l'ensemble du système. Pour estimer le niveau d'efficacité de l'amplificateur de puissance PA avec des signaux modulés, des mesures comme l'efficacité en puissance ajouté (PAE) peuvent être utilisées. Au niveau système, la mesure de l'efficacité moyenne est la plus fiable.

Ainsi, l'objectif principal consiste à développer et concevoir une architecture efficace de PA au niveau système destinée pour les téléphones cellulaires, les appareils portables et autres applications de communication sans fil tels que les réseaux large bande, tout en mettant l'accent sur l'amplification linéaire de puissance. Alors que les fréquences porteuses de ces applications vont de plusieurs centaines de MHz à quelques GHz, les puissances crêtes peuvent varier de 100 milliwatts à quelques watts. Les spécifications principales de l'amplificateur pour de telles applications sont: le coût, la réduction de la taille, le gain, la linéarité et l'efficacité en puissance. De plus, des critères comme la stabilité, la robustesse et la fiabilité sont à envisager.

Par ailleurs, les performances en linéarité des signaux transmis et reçus, peuvent être mesurées à l'intérieur et à l'extérieur de la bande du signal. En effet, l'erreur vectorielle d'amplitude (EVM) quantifie les effets de distorsion du système à l'intérieur de la bande, tandis que le niveau d'émission à l'extérieur de la bande, provoqué par les non-linéarités de l'amplificateur de puissance, est mesuré à l'aide du rapport de puissance de canal adjacent (ACPR).

En se Basant sur cette discussion, cette thèse vise à développer de nouvelles techniques d'amplification de puissance des signaux RF pour les systèmes de communication sans fil. La technique d'amplification proposée est une solution au niveau système offrant un rendement élevé tout en permettant de maintenir la linéarité du signal.

Les techniques d'amélioration de l'efficacité en puissance

L'architecture linéaire conventionnelle d'un transmetteur est basée sur un alignement simple de composants PA micro-ondes. Cet alignement se compose d'un modulateur de fréquence intermédiaire ou bande de base, un convertisseur et une chaine d'amplificateurs de puissance (en cascade). La chaîne d'amplificateurs en cascade se compose de plusieurs étages de gain en puissance avec des gains de l'ordre de 6 à 20 dB. Chaque étage doit garantir suffisamment de linéarité pour que le transmetteur puisse produire un signal modulé en amplitude ou un signal à porteuses multiples. Cela est généralement réalisé en utilisant des amplificateurs de puissance opérant en classe A avec un recule assez important dans les premiers étages. L'amplificateur de sortie opère de préférence en classe AB, puisqu'il présente la plus grande consommation de puissance DC. Dans certain cas, en dépit de la diminution de l'efficacité, il est nécessaire d'utiliser la classe A dans des applications exigeant un très haut niveau de linéarité.

Des solutions efficaces sont connues sous le nom de techniques d'amélioration de l'efficacité. Les trois techniques principales sont: 1) L'amplificateur Doherty, 2) L'amplificateur LINC (outphasing) et 3) la technique Kahn d'élimination et de restauration de l'enveloppe (EER). Ces trois techniques ont des applications potentielles dans les systèmes de communication sans fil et leur mise en œuvre avec facilité et efficacité au profit de l'expansion des technologies numériques est évaluée.

L'architecture LINC régulière 1X1

Les amplificateurs LINC sont proposés pour des applications où les transmetteurs doivent avoir une excellente linéarité, haute puissance et haute efficacité énergétique. Toutefois, l'architecture LINC souffre de certains problèmes au niveau de ses circuits tels que le déséquilibre des composantes entre les deux branches, ce qui provoque la dégradation du signal à la sortie du transmetteur. En outre, elle souffre de la dégradation de l'efficacité en puissance en raison de la recombinaison du signal, suite à l'amplification, à l'aide d'un combineur de puissance et surtout dans le cas des signaux à haut PAPR (Peak to Average Power Ratio). L'amplificateur LINC se compose d'un bloc de séparation des composantes du signal (SCS), qui divise le signal de base en deux composantes à amplitudes constantes et modulées en phase. Les deux composantes sont converties en signaux RF autour de la fréquence porteuse et par la suite amplifiées. Elles sont sommées par un combineur de puissance afin de reconstruire un signal RF modulé et amplifié, sans distorsion, tel que montré à la figure 2.

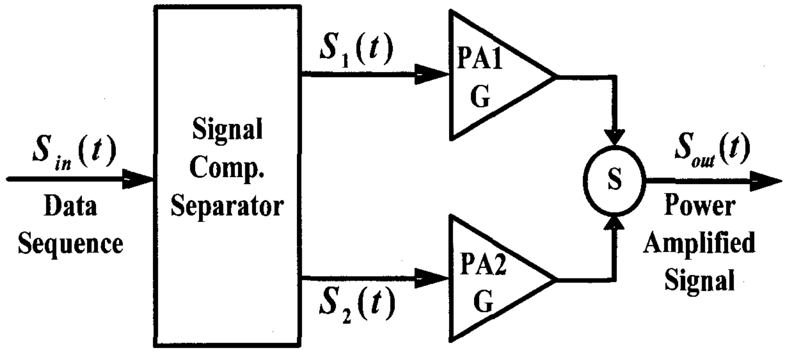

Figure 2: Architecture de l'amplificateur LINC.

La génération de signaux de branches implique un signal source à bande étroite, et un signal à large bande qui s'étend dans des canaux adjacents. Lors de recombinaison, les deux signaux sources sont ajoutés en-phase, tandis que les signaux à large bande s'annulent entre eux. Ceci suppose qu'il n'y a pas de déséquilibre en phase ou en gain dans les deux branches. En cas de déséquilibre, l'annulation n'est pas complète et les canaux adjacents sont affectés. Par conséquent, le processus de recombinaison exige plus d'attention. Puisque l'enveloppe des deux signaux de branche est constante, le LINC permet à l'amplificateur de puissance RF de fonctionner près de la saturation, ce qui, en principe permet d'obtenir une efficacité de puissance moyenne élevée.

Décomposition du signal LINC

Si un signal passe-bande avec enveloppe complexe $S(t)$ est utilisé et si, $|S(t)| \leq S_M$ avec S_M est la valeur maximum de l'enveloppe du signal, alors $S(t)$ peut s'écrire comme suit:

$$S(t) = S_1(t) + S_2(t) \tag{1}$$

où

$$S_1(t) = S(t)/2 + e(t) \tag{2}$$

$$S_2(t) = S(t)/2 - e(t) \tag{3}$$

$$e(t) = \frac{j}{2} S(t) \sqrt{\frac{S_M^2}{|S(t)|^2} - 1} \quad (4)$$

Le signal transmis est supposé être une réplique légèrement modifiée du signal d'entrée. Cela signifie que la sortie a une enveloppe complexe donnée par $GS(t)$, où G est le facteur de gain complexe de l'amplificateur comme le montre les figures 2 et 3. En raison d'un éventuel déséquilibre en phase ou en gain entre les deux amplificateurs, l'enveloppe complexe de sortie peut s'écrire comme suit :

$$S_{out}(t) = G_1 S_1(t) + G_2 S_2(t) \quad (5)$$

où G_1 et G_2 sont deux constantes complexes, éventuellement différentes.

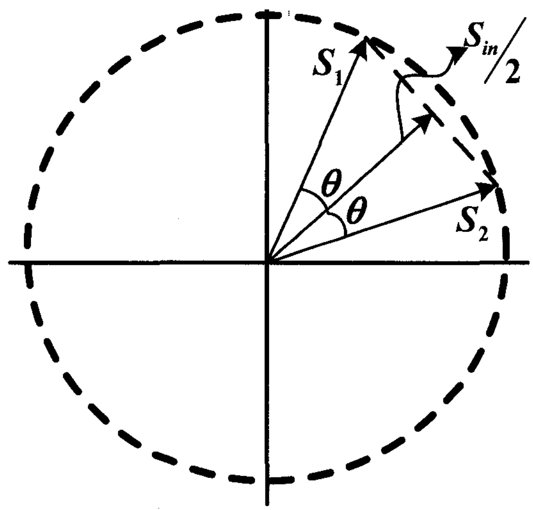

Figure 3: Décomposition du signal de l'amplificateur LINC.

Efficacités du LINC et technologies du combineur

L'efficacité moyenne de l'amplificateur LINC dépend de la dynamique du signal et de l'efficacité du combineur. Les deux types de combineurs utilisés sont le combineur hybride de puissance (Hybrid Power Combiner) et le combineur Chireix (Chireix

Outphasing Combiner). Le combineur de puissance isolé, à deux voies (hybride), résulte en une excellente linéarité, mais en même temps dégrade l'efficacité en puissance globale du système LINC.

En effet, le combineur Chireix est un combineur sans pertes qui améliore l'efficacité en puissance, mais dégrade la linéarité. Il a été démontré que les distorsions observées dans l'amplificateur LINC avec un combineur Chireix étaient inhérentes à la structure de recombinaison elle-même. Mais, en considérant un combineur hybride, il a été démontré que les sources de dégradation de linéarité étaient le déséquilibre en phase et/ou amplitude entre les deux branches du LINC et la non-linéarité intrinsèque de l'amplificateur. La troisième source de dégradation de linéarité est les filtres passe-bande dans la chaîne de transmission entre le circuit séparateur du LINC et les amplificateurs RF. Dans le cas de signaux a haut PAPR (< 10 dB), l'efficacité moyenne en puissance du transmetteur LINC peut être calculée selon la formule suivante:

$$\eta = \eta_a \eta_b \eta_c \tag{6}$$

où η_a est l'efficacité maximale de l'amplificateur, η_b est le rapport entre la puissance moyenne et la puissance de crête du signal, ce qui correspond à l'efficacité du processus de recombinaison du signal, et η_c représente les pertes transmission RF dans le combineur lui-même.

L'efficacité instantanée dans le cas du combineur hybride (combineur isolé et adapté), peut être calculée analytiquement est égalé a la fonction de $\cos^2(\theta)$ où θ est l'angle de décomposition. L'efficacité augmente à mesure que θ diminue, ce qui correspond aux crêtes du signal, comme l'illustre la figure 3. Également, tel que montré dans la figure 4, cette valeur diminue à mesure que θ augmente, ce qui correspond à des conditions de faible signal: c'est le cas le plus probable pour les signaux utilisés dans les systèmes de communication 3G et 4G comme le montre la figure 5. Dans la plupart des cas, lorsque l'amplitude du signal d'entrée est faible par rapport à l'amplitude constante des deux composantes générées, le combineur doit dissiper une quantité de puissance relativement grande pour être en mesure de reconstruire le signal à petite amplitude après amplification. Ceci implique évidemment une faible efficacité en puissance pour la technique LINC.

L'application du LINC à l'amplification des signaux de modulation OFDM étant introduite, la séparation des signaux de l'architecture LINC est ensuite implantée ainsi qu' un bloc de filtrage des signaux des branches utilisant un processeur DSP (Digital Signal Processing), comme le montre la figure 6.

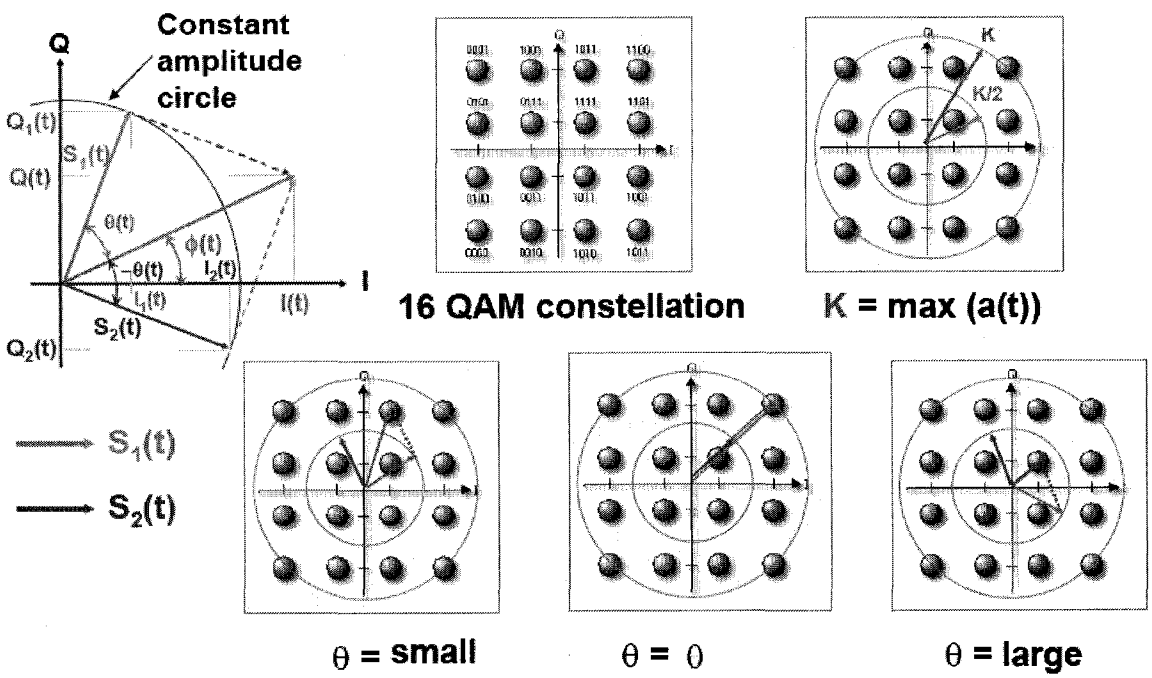

Figure 4: Décomposition du signal de l'amplificateur LINC, présentant différentes valeurs de θ [15].

Le LINC conventionnel est modifié par l'implantation en DSP des opérations de décomposition du signal et du processus du filtrage. Les signaux dans les deux branches du LINC sont filtrés afin de diminuer leur valeur d'ACPR et le rendre acceptable pour l'application WLAN 802.11.

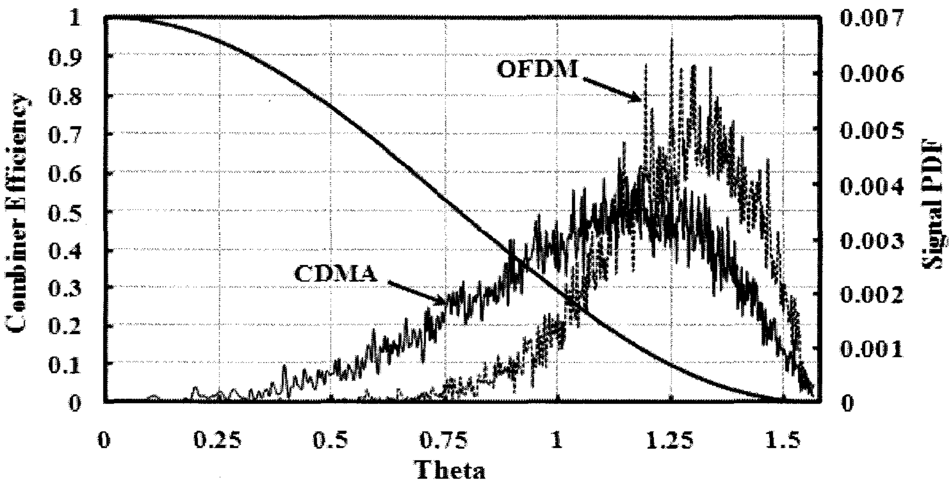

Figure 5: L'efficacité du Combineur hybride et PDF pour signaux modulés OFDM et CDMA vs. l'angle de décompositionθ.

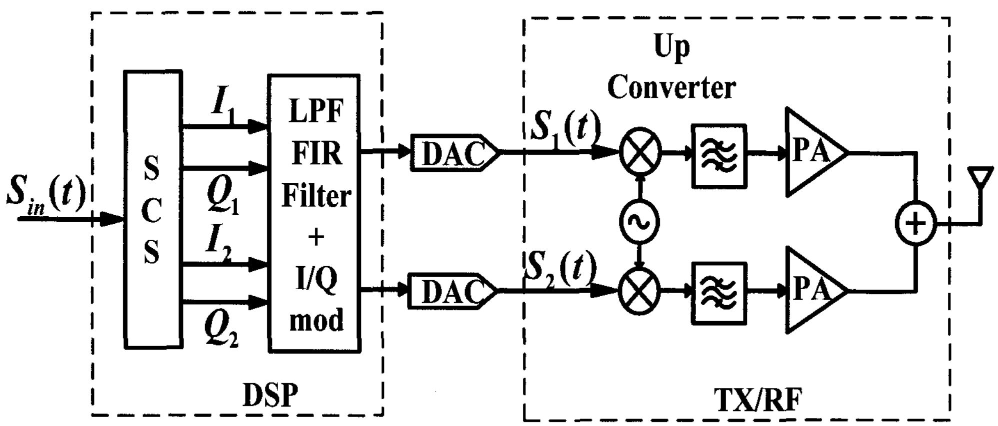

Figure 6: Un nouvel émetteur LINC FIR LPF bloc.

Lorsque l'ACPR est fortement réduit, des niveaux élevés d'interférence inter-canaux et des déséquilibres des branches du LINC peuvent être tolérés, comme le montre la figure 7. L'ACPR est amélioré par 43 dB lorsqu' un filtre des moindres carrés est utilisé. Les résultats du la simulation monteront que L'EVM obtenu dans ce cas est très proche de celui de LINC conventionnel (1.4%) et il est bien inférieur au seuil spécifié par la norme (5.62%). On peut donc conclure que l'opération de filtrage n'a pas affectée les performances du système en matière d'EVM et d'efficacité globale de puissance.

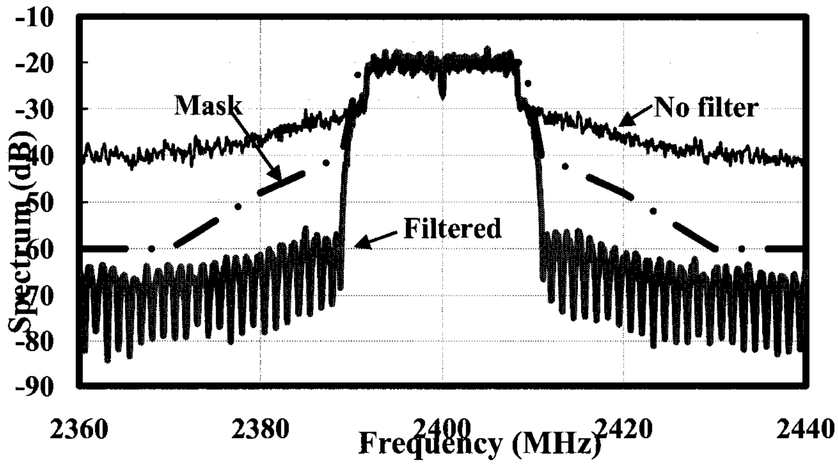

Figure 7: Spectre des fréquences du signal avant et après le filtrage d'un signal de la branche.

Emetteurs LINC Avancés (modifiés)

Une nouvelle architecture LINC pour les applications sans fil large bande est proposée. Elle est basée sur la modification de l'amplificateur LINC, dans lequel les signaux dans les deux branches LINC sont recombinés au niveau du récepteur afin de surmonter les problèmes liés aux pertes du combineur. Ainsi, le rendement global du système est amélioré. La nouvelle architecture proposée pour l'amplificateur de puissance RF a été simulée et les résultats démontrent l'amélioration de l'efficacité globale de puissance. D'abord, une nouvelle topologie dans laquelle deux antennes d'émission et une antenne de réception sont employées en gardant la même architecture du récepteur, a été testée afin de réduire la complexité du système. Il convient aussi de mentionner que, pour minimiser l'effet des déséquilibres entres les deux branches du LINC, cette nouvelle architecture utilise un système d'auto-adaptation. Elle est basée sur l'implantation DSP, où la séparation du signal d'entrée du LINC et le filtrage des signaux des branches sont effectués. La recombinaison du signal est effectuée au niveau de l'antenne de réception. Cette nouvelle disposition vise à surmonter les problèmes liés aux pertes du combineur de l'émetteur. Ceci est illustré à la figure 8.

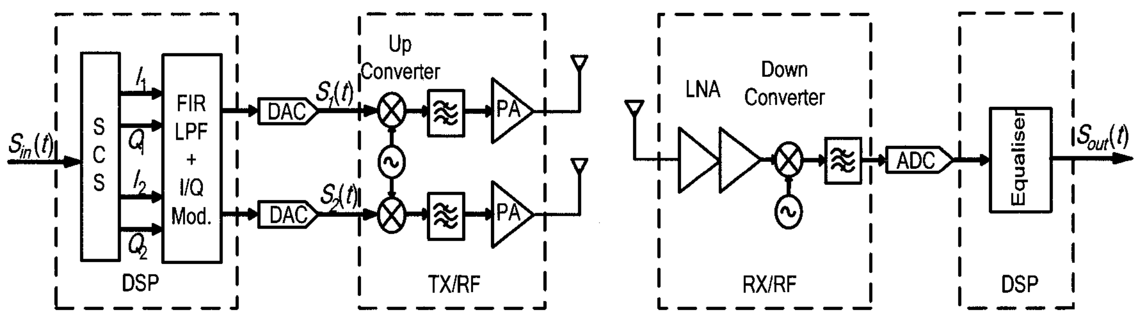

Figure 8: présentation détaillée du projet de système 2x1 LINC.

Les résultats montrent une amélioration au niveau du point d'opération en recul (BACK-OFF) de 9.4 dB et 3.66 dB par rapport au système à une seule branche d'amplification et l'amplificateur LINC conventionnel respectivement; Ceci engendre une efficacité de 16.17% pour le schéma proposé de LINC 2x1 et 4.72% pour les LINC conventionnel en comparaison avec 1.43% pour une seule branche d'amplification. L'EVM de l'architecture proposée est de 1,53%, ce qui est bien en dessous de la valeur maximale autorisée par le standard (5.6%). Dans ce système, les signaux dans les deux branches LINC sont filtrés pour s'adapter au masque de transmission et réduire leurs ACPR. La performance en termes d'ACPR est considérablement améliorée, ce qui permet d'avoir une marge dans les niveaux de l'interférence inter-canaux et les déséquilibres entre les branches du LINC. Et puisque le combineur du coté de l'émetteur est éliminé, l'efficacité du système entier est améliorée. Les résultats ont montré que l'ACPR a été amélioré de 43 dB, en utilisant le filtre des moindres carrés. En plus, l'efficacité du système a été améliorée de 3.4 fois par rapport à celle d'un amplificateur LINC. L'opération de filtrage n'a pas eu d'effet sur les performances du système en ce qui concerne l'EVM. Ce nouveau système 2x1 a l'avantage d'avoir une architecture standard de récepteur tout en offrant une amélioration de la performance du système en ce qui concerne l'efficacité, l'ACPR et l'EVM.

Par ailleurs, une architecture LINC avec deux antennes d'émission et deux antennes de réception (LINC 2X2) est présentée. Elle est représentée dans la figure 9. Les simulations ont été réalisées en supposant un canal idéal et un canal réel. Comme le PAPR des deux signaux des branches a augmenté de 0.0 dB à 3.0 dB à cause de l'effet de l'opération du filtrage, la linéarisation des deux amplificateurs a été nécessaire. La méthode de linéarisation DPD a été utilisée. Il a été trouvé que le filtre numérique de mise en forme à l'émetteur était efficace pour réduire l'ACPR. De plus, le point d'opération de recule de l'amplificateur a été amélioré de 5.6 dB par rapport à l'amplificateur LINC conventionnel. L'EVM mesuré pour le LINC 2X2 était de 0.54%, ce qui est très faible par rapport à l'EVM admissible de 5.6% spécifié par la norme IEEE 802.11g avec un débit binaire de 54 Mbps. Par la suite, un canal réel à deux chemins non corrélés grâce à l'utilisation deux différentes polarisations pour les antennes de transmission. Les résultats montrent que les performances de l'architecture proposée étaient supérieures à celle de l'amplificateur à une seule branche et de LINC conventionnel.

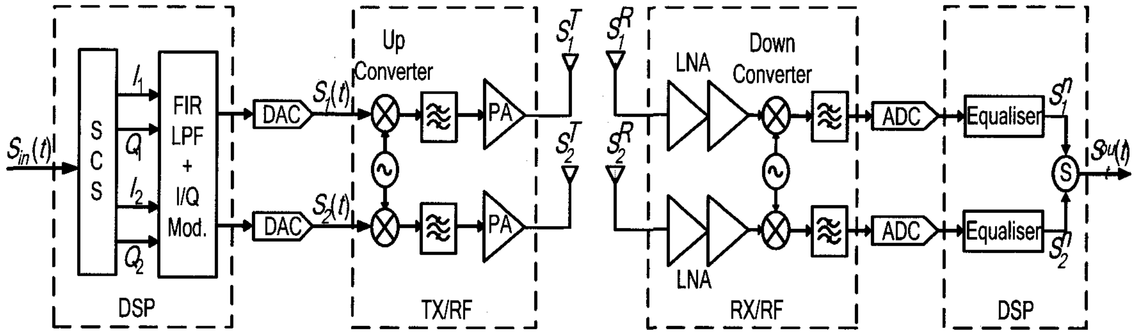

Figure 9: mise à jour LINC émetteur architecture.

Une valeur de 1.76% de l'EVM a été obtenue pour le système LINC 2X2. En outre, le point d'opération a été amélioré pour le LINC conventionnel et modifié par rapport à celui de l'amplificateur classique. Les résultats montrent que le point d'opération des amplificateurs a changé de 9.4 dB à 3.8 dB grâce à l'utilisation de la nouvelle architecture LINC. Ceci a impliqué un gain important à l'efficacité ajoutée variant de 5% à 18% pour les émetteurs pour le cas d'un signal 802.11g. Aussi, la perte du combineur est supprimée, augmentant ainsi l'efficacité globale moyenne de l'émetteur de 3.9% pour les LINC conventionnel à 15.5% pour la LINC modifié. Le niveau d'EVM calculé à la sortie de l'émetteur est de 1.76%, ce qui respecte largement la valeur maximale autorisée du standard (5.6% à 54 Mbps de débit binaire).

Conclusion et travaux futurs

Cette thèse a introduit deux nouvelles architectures pour l'amplificateur de puissance où il a été proposé, pour la première fois, d'altérer la conception de l'étage final de l'émetteur RF en utilisant une approche de conception au niveau du système. Cette approche a permis de remédier aux effets négatifs du combineur de puissance sur l'efficacité énergétique moyenne du système. Bénéficient du fait que les deux signaux peuvent être recombinés du côté récepteur, les architectures proposées requièrent la transmission des deux signaux des branches après avoir été filtrés et amplifiés.

Les résultats de simulation de la solution proposée montrent que ce nouveau transmetteur est une solution valable pour les systèmes de communication utilisant des signaux l'OFDM. Les résultats tirés suite à ce travail de recherche sont les suivants:

- Les signaux des deux branches ont été filtrés pour respecter les spécifications du masque de transmission du standard WLAN IEEE 802.11g.

- Différents filtres numériques passe-bas ont été testés. En particulier, le filtre des moindres carrés a donné des résultats optimaux pour l'architecture proposée.

- Les résultats de simulation, pour le cas d'un canal idéal unitaire, ont révélé une amélioration du point d'opération de l'amplificateur d'environ 3.6 dB pour le LINC modifié par rapport à 9.4 dB pour l'amplificateur classique. En outre, l'EVM a été estimé à 0.54%, ce qui était largement en dessous de la valeur de 5.6% autorisée du standard.

-La réponse de l'architecture LINC modifiée a donné des résultats satisfaisants lors des simulations avec un canal multi-trajets avec du bruit blanc. L'EVM a été d'environ 1.6% et le point de recul a été de 3.69 dB.

- L'efficacité énergétique moyenne du système modifié a été améliorée environ 11 fois par rapport à celle de l'amplificateur classique et environ 4 fois par rapport à celle de LINC conventionnel.

Contributions

Les principales contributions de cette thèse peuvent être résumées comme suit:

• L'ajout d'une étape de filtrage dans le bloc DSP réservé à la séparation du signal de l'amplificateur LINC, résultant en une amélioration de la performance du système d'amplification LINC en termes d'ACPR et de robustesse au déséquilibre entre les branches du LINC.

• L'introduction d'une nouvelle solution d'amplification au niveau système LINC 2X1 pour les standards de communication sans fil : Le LINC 2X1 est destiné à remplacer l'amplificateur LINC conventionnel afin d'éliminer le combineur du LINC qui est à l'origine de la dégradation de l'efficacité.

• La présentation d'une nouvelle solution d'amplification LINC 2X2, au niveau système, adaptée aux systèmes de communication.

• En plus de l'amélioration de l'efficacité, les deux nouveaux schémas proposés ont également amélioré la performance du système en termes d'ACPR et d'immunité au déséquilibre entre les deux branches.

Cette thèse est organisée en cinq chapitres : Le premier chapitre décrit le problème visé par le travail de recherche ainsi que la motivation et l'importance d'être considéré par les concepteurs des transmetteurs radio.

Le deuxième chapitre présente une étude qui concerne le problème de l'amplification de puissance dans les systèmes de communications sans fil. Les objectifs et les contributions de la thèse y sont aussi présentés.

Le troisième chapitre illustre les notions de base des standards des systèmes de communication sans fil ainsi que les technologies reliées aux amplificateurs de puissance. Les architectures utilisées pour les émetteurs RF sont aussi exposées. L'objectif commun entre les différents types d'amplification de puissance est l'augmentation de la durée de vie des batteries des terminaux portables ou d'améliorer l'efficacité de la puissance des stations de base. Chaque type est donc analysé du point de vue de l'efficacité et de la complexité.

Le quatrième chapitre s'intéresse à l'architecture de l'amplificateur LINC (LInear amplification with Nonlinear Components) conventionnelle. Les questions de conception liées aux performances de l'amplificateur de puissance basée sur l'architecture LINC, la décomposition du signal, les types de combineur et l'efficacité sont également couvertes dans ce chapitre. En outre, une nouvelle implémentation de l'architecture LINC, dans laquelle le signal est décomposé et les signaux des branches sont filtrés, est introduite. Les effets du déséquilibre des branches sont aussi étudiés.

Le cinquième chapitre propose deux nouvelles architectures modifiées du LINC, à savoir, le 2X1 et le 2X2. Les performances des nouvelles architectures sont présentées en mettant l'accent sur le rapport de puissance du canal adjacent (ACPR), l'efficacité, les effets des déséquilibres et les effets du filtre.

Dans le sixième chapitre, nous résumons les principaux points discutés au cours des chapitres précédents, et identifions des principaux domaines de recherche pour l'avenir.

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List of abbreviations

3G, 4G	Third, Fourth generation cellular systems.
802.11a/g	OFDM-based wireless LAN based on IEEE standard 802.11a, or 802.11g
802.11b	QPSK-based wireless LAN based on IEEE standard 802.11b
ACI	Adjacent Channel Interference.
ACLR	Alternate Channel Leakage Ratio.
ACPR	Alternate Channel Power Ratio.
BER	Bit Error Rate.
CDMA	Code Division Multiple Access.
CFR	Crest Factor Reduction.
CW	Continuous Wave
EDGE	Enhanced data rate for GSM evolution.
EVM	Error Vector Magnitude.
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FM	Frequency modulation.
FSK	Frequency Shift Keying
GaAs	Gallium Arsenide
GMSK	Gaussian Minimum Shift Keying
GaN	Gallium Nitride
GPRS	General Packet radio service.
GSM	Global system for mobile communication.
HBT	Hetrojunction Bipolar Transistor
HEMT	High Electron Mobility Transistor
HFET	Hetro-Structure FET.
InP	Indium Phosphide
IS-95B	Interim Standard 95B (original CDMA standard).
LINC	LInear amplification using Nonlinear Components

MMIC	Monolithic Microwave Integrated Circuit
MIMO	Multi Input Multi Output.
OFDM	Orthogonal frequency division multiplexing.
OQPSK	Offset Quadrature phase-shift keying.
PA	Power Amplifier
PAE	Power Added Efficiency
PAPR	Peak to Average Power Ratio.
PCS	Personal Communication System.
pHEMT	Pseudomorphic High Electron Mobility Transistors
PSD	Power Spectrum Density.
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying.
SiC	Silicon Carbide
SHF	Super high Frequency
SSB	Single Side Band
TDMA	Time Division Multiple Access.
UMTS	Universal mobile telephone service.
VHF	Very high Frequency
VLF	Very Low Frequency
W-CDMA	Wideband code division multiple access.

Chapter 1

INTRODUCTION

1.1 Research overview

Wireless communication has become the most important communication mean and its use has increased dramatically over the last decade, due to the high demand on communication systems capable of providing easier connectivity anywhere and anytime with high data transfer rates. On the other hand, wireless systems are now used for computer networking and internet access in addition to voice/video communications. Moreover, the emphasis has shifted from providing fixed voice services to general wireless digital services that allow a wide variety of applications [1]-[6]. As a consequence of this growth, the need to develop new higher-capacity and highly reliable communication systems is increasing and driving research work to develop more integrated services, providing higher data rates and more universal interface for a variety of applications.

In addition to this the available crowded spectrum is forcing the use of complex modulation technique and multiple access schemes in which the generated complex signals resulting from adopting these schemes are associated with increased signal dynamics. Therefore, they require highly linear power amplifier (PA) characteristics to reduce out-of-band radiation levels which impose more challenges on the design of linear RF PA systems [2], [7], [8] and [9]. The goal of improving the inherent design trade-off between efficiency and linearity for such systems is very important and has been a great deal of interest to develop advanced amplification architectures. A survey of the research works carried out in this area shows that the design for efficiency was tackled on the device/circuit level (like using different operation classes), on the architecture level (different architectures for improved efficiency and linearity), and finally on the system level.

Conventional PAs have been designed on device/circuit level. This circuit level design was constructed using different classes of operation in simple linear amplification and power combining layouts which were used and are still in use. Examples of such architectures are simple line ups, multi-stage PAs, push-pull PAs, balanced PAs, and power combined PAs. However, in order to design PAs that meet certain efficiency and linearity requirements, both architecture and system level based PA designs come in selection. In the case of designing for efficiency, architectures like stage bypassing, Kahn, envelope tracking, LINC (LInear amplification with Nonlinear Components) and Doherty are viable [10], [11]. Moreover, in the design case for linearity, architectures like feedback, feedforward and predistortion (RF and digital baseband) are common [10],[11], [12] and [13].

These layouts do exist, but they have limitations either in bandwidth or in the dynamic range over which the efficiency is improved [10]. On the system level category, the combination of one of the mentioned architectures with DSP (Digital Signal Processing), to implement an adaptive amplification system with higher efficiency and linearity is nowadays a driving force for more research work as reported in [1], [7], [11] and [14]. In what follows, a simple introduction to the above mentioned architectures will be presented.

1.2 Research problem

Efficiency of microwave power amplifiers is the most critical factor affecting the overall system power dissipation. Most approaches to improve amplifier efficiency result in a loss of linearity, which is unacceptable for communication systems employing advanced spectrally-efficient modulation techniques. Also, as the main disadvantage of the new complex modulated signals, like OFDM, is that the signal peak may rise up to ten times the average power, the transmitter's amplifier will be forced to operate in the nonlinear region and thereby causing inter-modulation distortions and BER increase [14], [15] and [16].

In this dissertation, the main goal is to develop and design an efficient system level PA architecture for cellular phone handsets, portable wireless devices, and other wireless communication applications with emphasis on linear power amplification. CDMA and OFDM based systems are also among these related applications. While the carrier frequencies in these applications range from several hundred MHz to few GHz, peak powers ranging from 100 milliwatts to few watts are common. The most general objectives and specifications in an amplifier design for such applications are mainly controlled by parameters, such as cost, size reduction, gain, linearity, and power efficiency. In addition, criteria like stability, robustness, reliability, etc should also be considered.

1.3 Thesis objectives and contributions

This research project consists of studying and developing new transmitter architectures with emphasis on topologies that can meet today's linearity and high efficiency requirements. In this study, a new system level solution for the power amplification front end in wireless communication transmitters is proposed. The new topology is intended for efficiency enhancing. Indeed, it adopts a new LINC architecture that overcomes the conventional LINC efficiency degradation problems due to the combiner losses [15], [17], [18], [19], and [20] by transmitting the two RF amplified branch signals and combining them at the receiver instead of combining them at the transmitter [25][26][27][28] and [28]. Accordingly, the LINC architecture efficiency is improved, while sufficient linearity for modulated signals such as OFDM modulated signals is secured. Therefore, the overall system power efficiency is enhanced.

The system operation, in brief, is as follows: the baseband OFDM or CDMA signal to be transmitted are decomposed into two constant amplitude out-phased waveforms according to the LINC concept [11], [17]. The two branch signals are filtered (i.e. shaped to follow the transmission mask), up-converted, amplified using highly efficient nonlinear power amplifiers, and then transmitted using two transmitting antennas. The received signals are frequency down-translated before being converted to digital format for receiver processing purposes (equalization for the channel and correction of imbalance effects). Finally, the two signals are summed at the receiver side. This new architecture has the advantage of using two nonlinear amplifiers working in their high efficiency operation region (i.e. saturation region). This architecture alleviates the transmitter's combiner efficiency problems and also adds flexibility at the system level by compensating, in digital baseband equalization processing module, for the signal distortions due to the transmission channel effects and LINC branches imbalances [25], [26] and [27].

1.4 Thesis outlines

Based on this focus, this dissertation is arranged in six chapters. The current chapter had presented the research overview, definition of the research problem, thesis objectives, and contributions. Chapter 2 will present the necessary background for wireless communications and the new trends in the field. The assessment of the performance of the communication system is also to be presented with a discussion about the linearity and efficiency concerns. Chapter 3 will introduce a brief overview of power amplifiers as well as the related technologies and architectures used for RF and wireless transmitters. The common objective among these schemes is to enhance the talk time of portable terminals or increase the power efficiency for base stations. Each scheme is analyzed from efficiency behavior and complexity viewpoints. Chapters 4 will focus on LINC amplifier architecture as conventionally described. Also, design issues related to LINC based power amplifier performance and its robustness to branch imbalance will be investigated and solution to the problem will be proposed. Chapter 5 will propose two new modified transmitter architectures: the 2X1 and the 2X2 LINC based transceivers. A presentation of the performance of the new architectures is to be introduced with emphasis on ACPR (Adjacent Channel Power Ratio), efficiency, mismatch, and filter effects. In Chapter 6, the conclusion will summarize the main points discussed in the previous chapters. Main areas for future research will also be identified.

CHAPTER 2

BACKGROUND AND COMMUNICATIONS TRENDS

2.1 Introduction

As the communication systems are moving towards the wireless media, the need for efficient modulation techniques and more power efficient systems is pushing. In fact, some efficient modulation techniques have been proposed, but the problem associated with them is how to amplify the resulting modulated signals and transmit them in a linear and efficient manner. In what follows the new trends of wireless communication and an introduction of the different modulation techniques is introduced, with emphasis on OFDM. In addition, the parameters used to govern the performance of the system are also introduced concerning linearity and power efficiency.

2.2 Wireless communication trends

The need to develop systems with higher transmission capacity and higher speed of access has led to the development of different generations of wireless communication systems like the first, second and third generations (1G, 2G, 3G). Besides, research activities aiming at developing the 3.5G and 4G generations have been intensified during the last five years [29], [30] and [31]. Therefore, computer wireless networks are also getting more attention motivated by the need for higher data rate, easier connectivity and more mobility. The evolution process in communication and electronic fields has resulted in introducing new technologies and standards which facilitate the implementation of systems with improved properties. The aim is to overcome the limitations resulting from the utilization of the multiple access techniques like CDMA and OFDMA, which are introduced in modern wireless applications to better use the limited and overcrowded Radio Frequency (RF) spectrum [14], [32].

2.2.1 Modulated signals characteristics

Modern wireless communication systems are using complex digital modulation schemes, such as Quadratic Amplitude modulation (QAM), to address the increasing demand for power efficiency. However, these schemes are inherently not power efficient due to the resulting high PAPR and envelope magnitude varying signals. Also, in order to make use of the available spectrum, the design of the system has to take care of the emissions caused by the transmitted signal in the adjacent channels. In fact, the larger the signal emissions in the adjacent channel frequency band, the greater the distortion in the adjacent users' channels [35]. In wireless systems, this results in a reduction in the number of active users who can operate at the same time. Also, these distortions increase the BER due the accumulation of noise introduced into other users' channels. Therefore, new systems employing multiple access techniques (e.g. OFDM) have to be designed under strict requirements on transmitted signal linearity [6], [36] and [37].

2.2.2 Multiple Access Techniques

Since the bandwidth allocated to any radio system is always limited, multiple access schemes are used to allow many users to simultaneously use the same fixed bandwidth radio spectrum. For mobile phone systems the total bandwidth is typically 50 MHz, which is split into two halves to provide forward and reverse links. Sharing the spectrum is required in order to increase the user capacity of a wireless network. FDMA, TDMA and CDMA, depicted in Figure 2-1, are the three major methods of sharing the available bandwidth between multiple users in wireless systems. There are many extensions and hybrid techniques for these methods, such as OFDM and hybrid TDMA and FDMA systems. The idea about the basic methods is required to understand its variants [2], [3], [6] and [9].

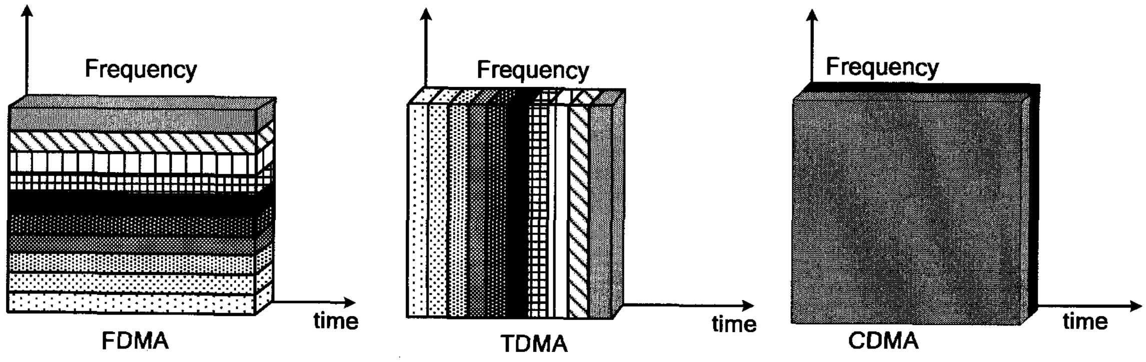


Figure 2-1: Multiple Access Schemes (FDMA, TDMA and CDMA).

In the FDMA case, the bandwidth is divided into a number of sub-band channels as shown Figure 2-2. A unique sub-frequency band is allocated to each user in order to be used for the both emission and reception. Precisely, the user's mobile station gets forward and a reverse link channels from the base station and vice versa. FDMA is considered the primary subdivision for large allocated frequency bands and is used as a part in most multi-channel systems. Typically up to 50% of the spectrum is wasted due to the extra spacing between channels. This problem is worse as the channel becomes narrower and the frequency bandwidth decreases. In the case of most digital phone systems where coders are used to compress the digitized speech, system capacity is increased due to the bandwidth reduction required for each user. FDMA would not be able to handle efficiently such narrow bandwidths.

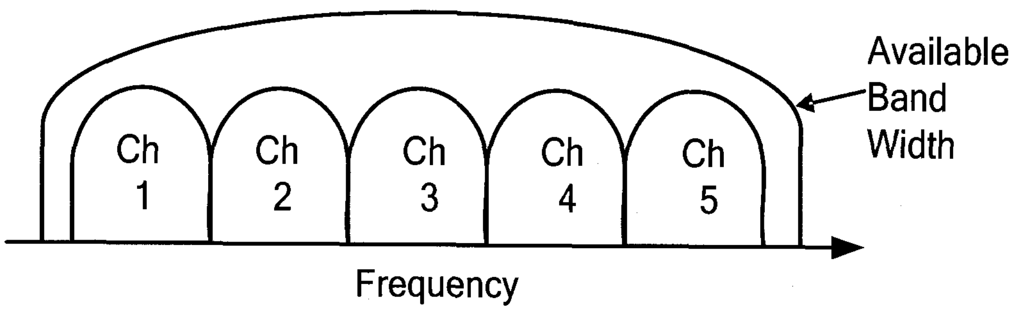


Figure 2-2: FDMA spectrum, the available bandwidth is subdivided into narrow channels.

On the other hand, in TDMA, the spectrum is divided into multiple time slots, each user is assigned a time slot in which he can transmit and receive. Figure 2-3 shows users assigned time slots (in a round fashion), considering that each user is allocated one time slot/frame.

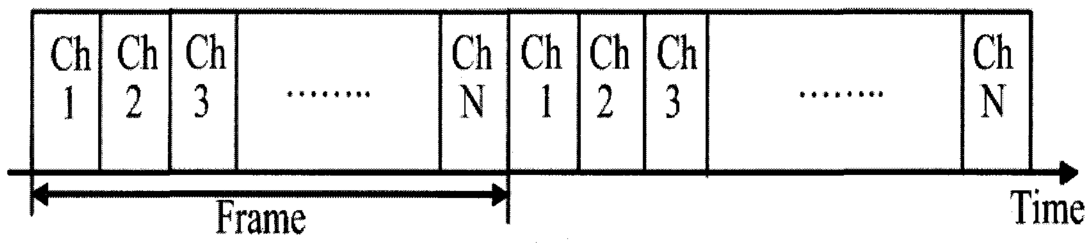


Figure 2-3: TDMA scheme where each user is allocated a small time slot.

Since TDMA uses a buffering scheme, it can't transmit analog signals directly. It should be converted to digital format first. TDMA suffers from multi-path effects, and as it has very high transmission rate, high inter-symbol interferences may occur. TDMA is usually used with FDMA to divide the available bandwidth into several sub-channels. This allows more users per channel and lower data rates. The effect of delay spread is reduced on transmission. In this hybrid scheme the bandwidth is first divided based on FDMA technique and then each channel is further divided using TDMA, so that several users can transmit using the same channel. This transmission scheme is used in 2G mobile phone systems. For example, in GSM, the assigned bandwidth (25MHz) is divided into 125 channels (of 200 kHz bandwidth) using FDMA, these channels are then subdivided using TDMA so that each 200 kHz channel allows 8 to 16 users.

Besides, in CDMA, which is a spread spectrum based technique, the narrow band data (normally digitized voice data) is multiplied by a large bandwidth signal which is a PN code (Pseudo random Noise code). All users use the same frequency band and transmit in the same time. The receiver then recovers the transmitted signal by correlating it with the same code used by the transmitter.

CDMA was originally developed for military applications to secure transmission in the presence of jamming, so for many years the spread spectrum technique was considered for military applications only. However, with the development of the integrated circuits and the introduction of LSI and VLSI designs, commercial systems have began to use these schemes in commercial applications. The main advantages of the CDMA are: interferences avoiding by signal coding, information security, accurate ranging, and mutable user access [3], [5].

2.2.3 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a multicarrier transmission scheme in which the available spectrum is divided into many carriers and each sub carrier is modulated using a low data rate stream. OFDM is very similar to FDMA as multiple users access the available spectrum in the same technique. However, OFDM uses the spectrum more efficiently by allocating the channel tightly close to each other. This can be achieved by making all carriers orthogonal to each other, preventing the interference between the closely spaced carriers, i.e. in OFDM; carriers are employed in such a way that the corresponding value of one carrier is zero at the center frequencies of the other carriers [4]. The resultant composite signal is shown in as shown in Figure 2-4.

OFDM splits the available bandwidth into many narrow band channels (100-8000 channels). In this way, OFDM allows many users to transmit in an allocated band by subdividing the available bandwidth into many narrow bandwidth carriers. As the carriers in each channel are made orthogonal to each other there is no need for the users to be time multiplexed as in TDMA and therefore there is no overhead associated with switching between users. In fact, the value of each sub-carrier has a null at the center frequency of each of the other carriers in the system to ensure no interference between carriers. The OFDM has a high tolerance to multi-path signals and is spectrally efficient. Hence, it is considered as a good candidate for the future wireless communication systems [6]. Also, with OFDM different modulation schemes can be used to modulate the sub channels carriers for layered services.

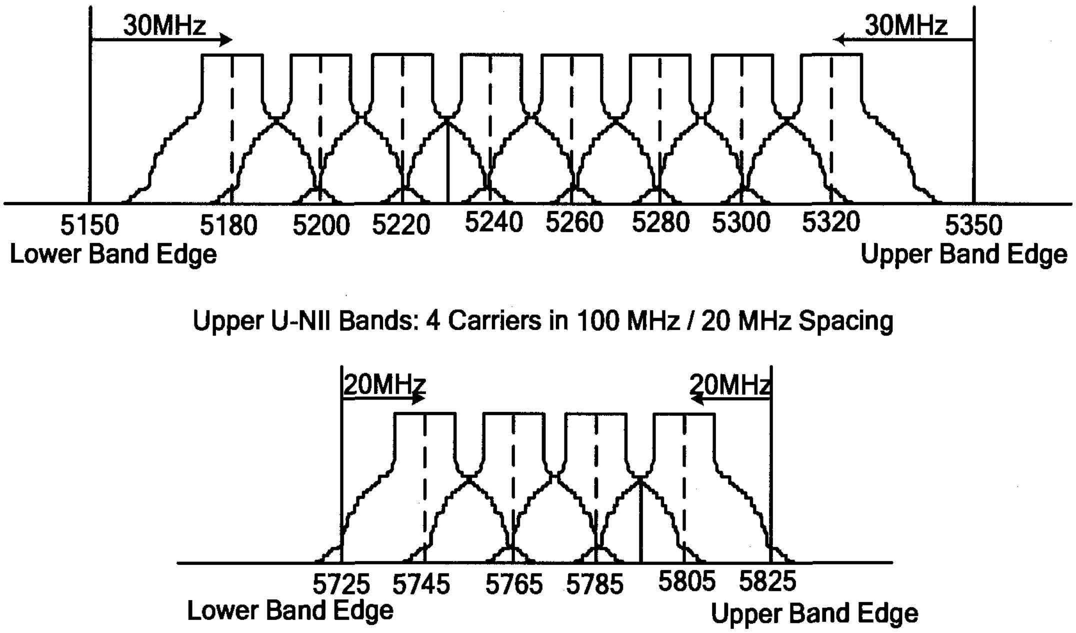


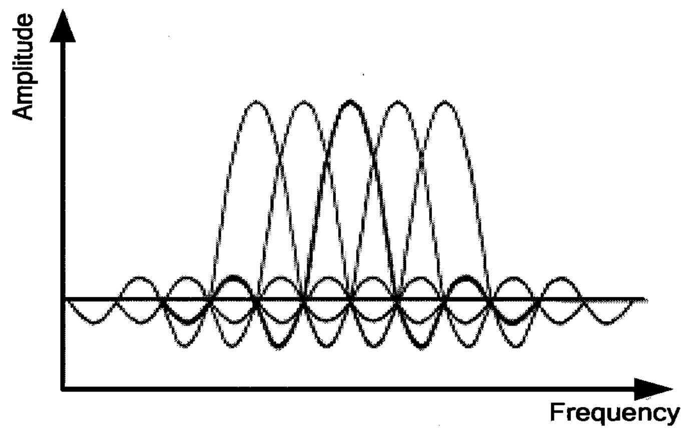
Figure 2-4: OFDM physical frequency channel plan.

However, as a modulated signal, the main disadvantage of the OFDM is that the signal peak can be up to 50 times the average signals power. The large peaks increase the amount of inter-modulation distortions resulting in an increase of the BER. The average signal power must be kept low in order to reach the limitation set by the transmitter's design [7][38] and [39].

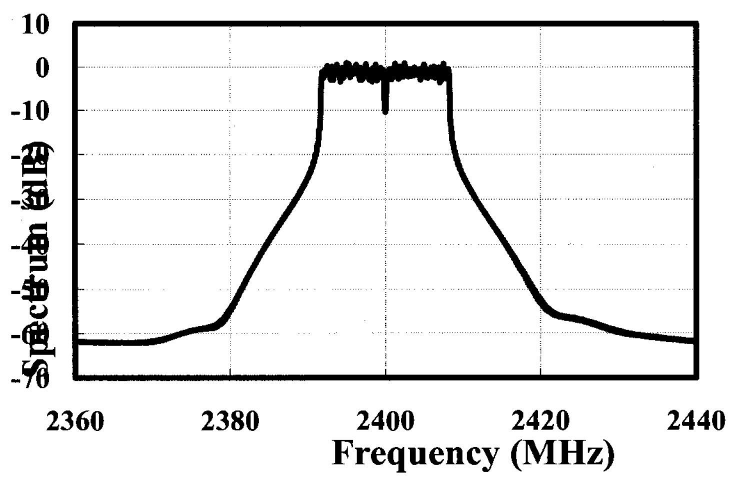
The complex Envelope of OFDM signal after (IFFT) is given as [7]:

$$S_{in}(t) = \sum_{K} \sum_{n=-N/2}^{N/2-1} x_k^{(n)} e^{j2\pi nt/T_s} rect\left[\frac{t-k(T_S+T_G)}{T_S+T_G}\right] \tag{1}$$

where: $1/T_S$ is the sub-carrier spacing, N is the number of sub carriers (Number of Data elements/Symbol to be sent), T_G is the guard interval to cope with multipath propagation effects. K is the number of symbols in time, and $x_k^{(n)}$ are the coefficients which are selected according to data and the modulation scheme for each subcarrier. Figure 2-5 shows the OFDM complex signal, where part (a) depicts the carriers with orthogonal frequency spacing, while part (b) shows the power spectrum of the OFDM signal.



(a)



(b)

Figure 2-5: OFDM composite signal, a) Carriers with orthogonal frequency spacing, b) OFDM signal power spectrum.

2.3 Performance measuring of a communication system

There exist different metrics which are used to evaluate the performance of a wireless digital communication system. As illustrated by Figure 2-6, these performance metrics can be generally divided into two main classes, those measuring efficiency and those measuring linearity. Efficiency performance is measured on both PA and system levels. PA level efficiency measures, like PAE (Power Added Efficiency), can be applied. For the system level, the average and instantaneous efficiency metrics are viable [9], [12],[40].

On the other hand, the linearity performance of the signals for such systems is evaluated for the in-band and out-of-band performances. Different linearity metrics are used to measure the in-band performance of the system, while others are related to the out-of-band performance. The EVM quantifies the in-band distortion effects of the system. The out-of-band emission level, caused by the power amplifier nonlinearities effect, is measured using the ACPR [29], [41].

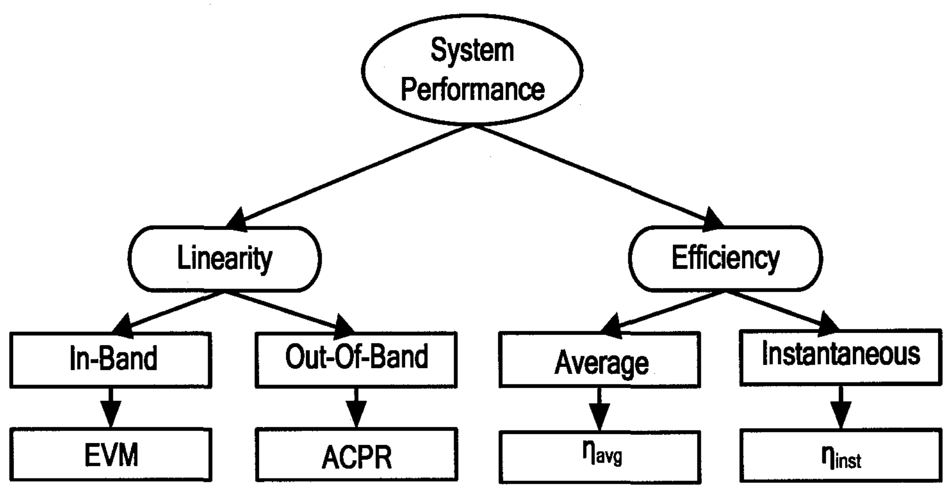


Figure 2-6: Performance metrics for a communication system.

2.3.1 Linearity and efficiency concerns

Distortion of RF signal can be described as an imperfection of the waveform of the ideal one. For efficiency purposes, RF amplifiers are generally used in the non-linear region causing distortion at the output. The non-linearity of an amplifier is the side effect of the deviation from the ideal linear amplification, when the input power of the amplifier is increased [20], [42]. For a linear amplifier, the output voltage is related to the input voltage by:

$$v_o(t) = G * v_i(t) \tag{2}$$

where G is the gain of the amplifier. In practice, this is possible only up to the saturation level of the amplifier. An Amplifier starts clipping once it reaches its saturated output level. This clipping generates non-linearity distortions. So, it can be said that amplifier's design can present several challenges related to power efficiency and linearity in addition to the gain and dynamic range. These limitations will force design engineers to think about a compromise between linearity and efficiency [30].

Power amplifiers are inherently nonlinear systems, because the large signal behavior of the semiconductor devices is itself nonlinear. Figure 2-7 shows some common measures that are used for characterizing the PA nonlinear behavior such as the 1dB compression point (P_{1dB}) and the third order interception point IP3. The 1 dB compression point (P_{1dB}) is the output power value where the difference between the amplifier linear gain and actual nonlinear gain is equal to 1 dB. The IP3 is the extrapolated interception point between the desired linear outputs with the 3rd order inter-modulation with two-tone excitation [12].

The P1dB and IP3 measures are independent of input signal modulation schemes. In addition to the amplitude (AM-AM) nonlinearity shown in Figure 2-8, power amplifiers usually exhibit amplitude to phase conversion behavior (AM-PM), as depicted by Figure 2-9. AM-(to)-PM refers to the creation of phase modulation (PM) observed at nonlinear amplifier's when fed with an amplitude modulated (AM) signals. AM-PM is often the result of voltage dependent capacitors (e.g. junction capacitors).

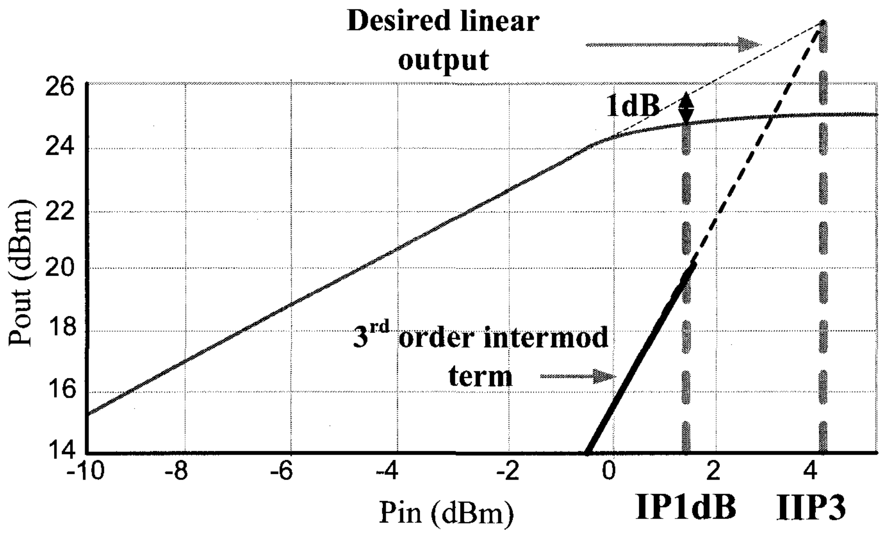


Figure 2-7: Output power vs. input power curve showing P_{1dB} and IP3.

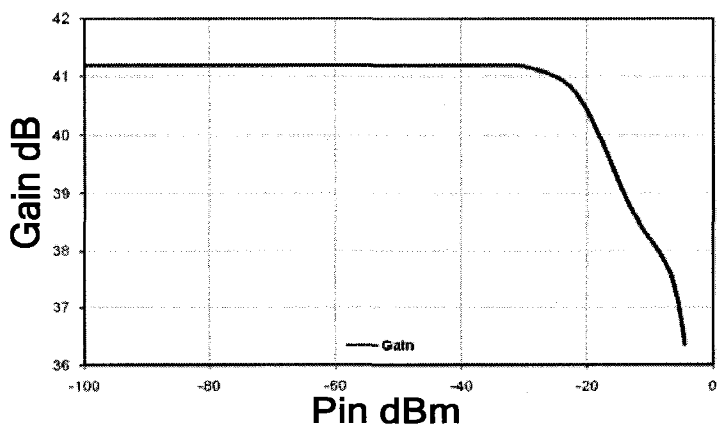


Figure 2-8: AM-AM curve for PA.

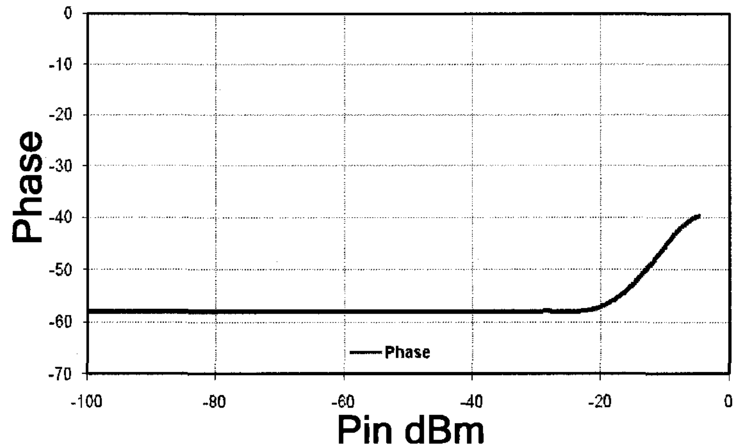


Figure 2-9: AM-PM curve for PA.

Actually, the efficiency of microwave power amplifiers is one of the most critical factors affecting the system overall power dissipation. Therefore, losses in mobile terminals batteries and for satellite communication transmitters and transponders are a critical issue. Besides, PA efficiency is affecting the operating power consumption of the base stations and repeaters, thus affecting the running costs of these stations. Most approaches used to improve amplifier's efficiency need a sacrifice in linearity, which is unacceptable for communication systems employing advanced and spectrally efficient modulation techniques. The linearity and efficiency goals, in addition to the high frequency operation (2.4 GHz to 5-6 GHz, in recent applications and above in the future), provide a set of constraints for the power amplifiers designers [7][15], [20] and [44].

2.3.1.1 Linearity

One of the main concerns in modern PAs design is the need for linearity. Constant envelope (amplitude) signals such as CW, FM, classical FSK, and GMSK (used in GSM) do not require linear amplification. However, when the signal contains both amplitude and phase modulation, linear amplification is required. SSB voice, sideband television (NTSC National Television System Committee and HDTV High Definition

TeleVision), modern shaped-pulse data modulation (QAM, QPSK, CDMA) and multiple carriers (OFDM) are examples of such signals [6].

In addition, the use of shaped data pulses in modern wireless communication systems, such as QPSK, QAM, OFDM and CDMA, is necessary to address the increasing requirements for both high data rates transmission and efficient utilization of the increasingly crowded spectrum. It is more convenient to use a large number of low data rate carriers rather than a single high data rate carrier.

The resulting time domain OFDM signals may have a peak-to-average ratio in the range of 6-17 dB [1]. Both amplitude nonlinearity AM-AM (variable gain) and amplitude-to phase conversion AM-PM resulting from the power amplifier can cause distortions of the amplified signal. This would result in energy spreading into adjacent channels and impairment of detection. There exist many techniques that can be used to improve the linearity like feedback, feedforward, predistortion, and LINC [10], [12].

Various techniques are used to characterize measure and specify linearity depending on both the signal and the application. The carrier-to-intermodulation (C/IMD) ratio compares the amplitudes of the desired output carriers to the intermodulation-distortion (IMD) products. ACPR compares the power in an adjacent channel to that of the signal. Also, EVM which can be defined as the distance between the ideal and actual constellation symbols is a widely used metric in 3G and WLAN RF communication systems [21], [35].

2.3.1.2 ACPR performance

It is worth mentioning that the amplitude dependent amplifier nonlinearities interacting with modulated carriers having variable envelopes cause an effect called spectral regrowth. In fact, modulated carriers can be considered as a large set of tones squeezed into a particular frequency band around the carrier. Amplifier nonlinearity creates intermodulation products among these tones. These result in the creation of additional unwanted spectral components called spectral regrowth [45]. Figure 2-10 shows a typical spectrum of a nonlinear amplifier output suffering from spectral regrowth.

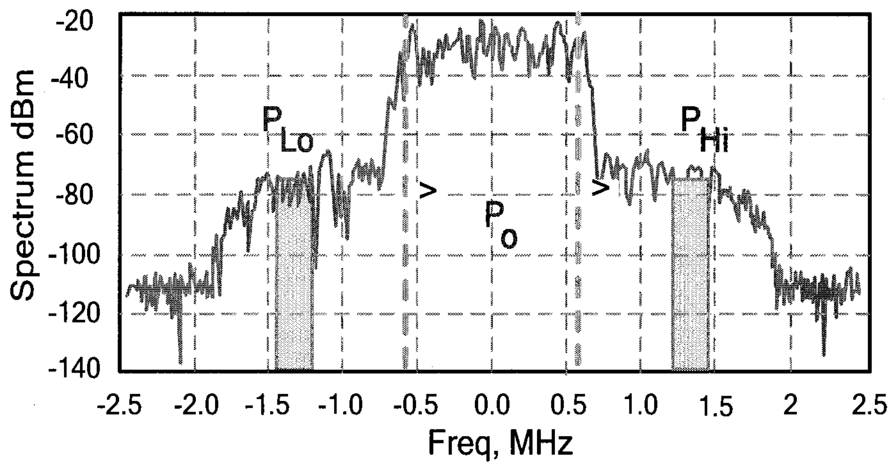


Figure 2-10: Spectral regrowth problem.

The ACPR measures the unwanted signal emission to adjacent channels (spectral regrowth). It is defined as the ratio of unwanted power created in a specific channel within a specified bandwidth at a specified frequency offset from the main carrier to the power in the desired modulation bandwidth. This term is very often faced as regulatory parameter by the FCC. Adjacent and alternate channel limits could be read from the spectrum. For example, in PCS CDMA (IS-95) [46], ACPR is defined as the ratio of the power in a 30 kHz bandwidth at 1.25 MHz offset from the center frequency to the power in the main modulation bandwidth. For typical WLAN 80211a/g, ACPR limit is defined as -40 dB for neighboring channel and -20 dB for the alternate channel relative to channel power. Channel power is measured in 20 MHz bandwidth and the same principle is applicable for alternate and adjacent channel. Equations (3) and (4) give the value of the ACPR for the lower and higher offsets from the center frequency.

$$ACPR_{HI} = \frac{P_{HI}}{P_o} \tag{3}$$

$$ACPR_{LO} = \frac{P_{LO}}{P_o} \tag{4}$$

Unlike P_{1dB} and IP3, ACPR and other spectral regrowth based nonlinearities' measures are heavily dependent on the signal's modulation. As a result, using specific signal characteristics and statistics is very important in simulating or measuring ACPR in nonlinear systems. In this research work the ACPR is used to measure out of band emissions of the proposed systems and compared to the standard and other existing systems, [25], [33] and [45].

2.3.1.3 Efficiency

As stated before, in case of linearity, efficiency is a critical factor in RF and microwave power amplifiers design. Power amplifiers are devices that amplify the input RF or microwave signals and deliver much higher power at the output. Their efficiency can be measured with different metrics. Power gain, which is defined as the ratio of the output RF power to input RF power, is considered as a primary performance measure. The power amplifier can also be perceived as a device that converts DC power provided from the supply into RF power at the output. One of the most critical performance measures of a PA is the efficiency of this conversion process. Drain or collector efficiency is defined as the ratio of RF output power to the DC power provided from the supply. There are three definitions for efficiency most commonly used [10], [12]:

1) Power or drain/collector efficiency,
2) Power-added efficiency (PAE),
3) Overall efficiency (system efficiency).

The stated efficiency metrics are commonly used to measure the amplifier efficiency. For communication systems involving amplitude modulated signal having high PAPR, the average efficiency is considerably lowered in comparison to a continuous signal response. That is, of course, different from the instantaneous efficiency which depends on the power level.

As non-linearities in the PA distort the signal being amplified, it results in splatter into adjacent channels in the transmission stage and error in detection at the receiver side. To overcome these problems while achieving good linearity, the PA should be used in the linear region (i.e. a large back-off is needed) and thus lowering the overall efficiency. At high transmission power levels, poor efficiency results in high power consumption, heat generation and poor reliability. Therefore, the base-station operating cost is increased due to the high power consumption of the cooling systems.

On the other hand, as the power amplifier dissipates a major portion of the total power in many portable systems such as phone handsets, the efficiency of that amplifier is the most important factor affecting the talk or operation time thus. This results in lowering the battery life for mobile units. Figure 2-11 and Figure 2-12 show the behavior of a typical power amplifier with the regards to the compression curve and the power added efficiency. A rather good general review of these basic concepts on RF power amplifiers can be found in [1].

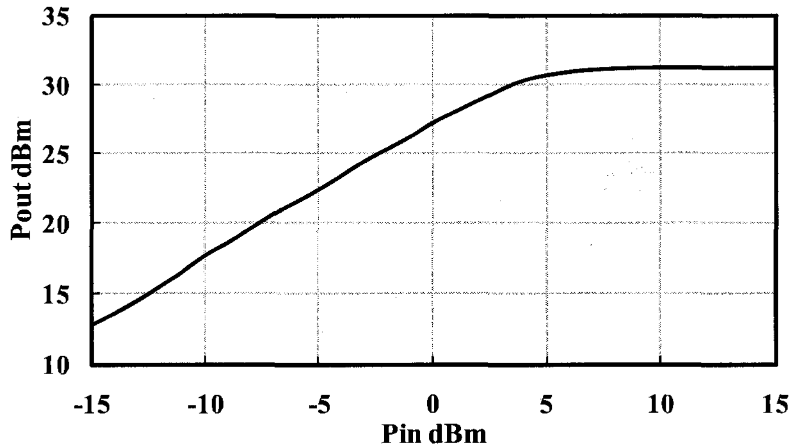


Figure 2-11: Output power compression versus input power curve.

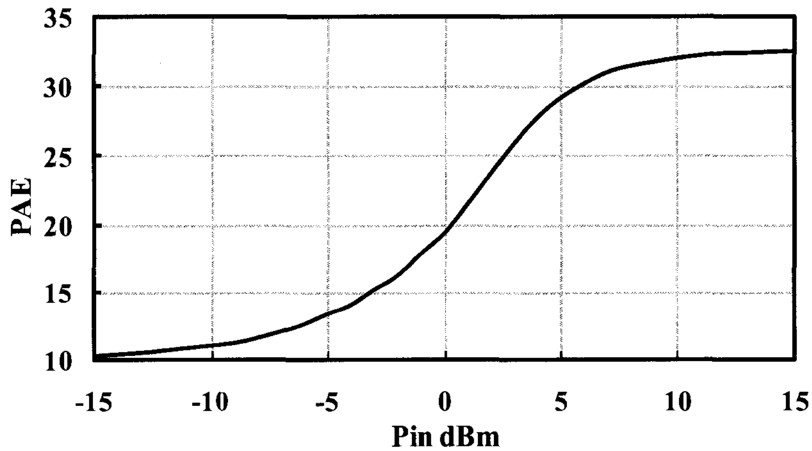


Figure 2-12: Power added efficiency as a function of input power.

With the fact that, the new modulated techniques information-bearing waveforms exhibiting PAPR (Peak to Average Power Ratio) that exceeds 10 dB. These non constant envelope modulation techniques require that the PA be operated in its linear region to prevent spectral splattering, keeping signals linearity. So, the PAs should be backed-off from their most efficient region (i.e. saturation region), loosing in efficiency. Thus, a good tradeoff between the efficiency and the linearity needs has to be performed. The conflict between linearity and efficiency is illustrated in Figure 2-13.

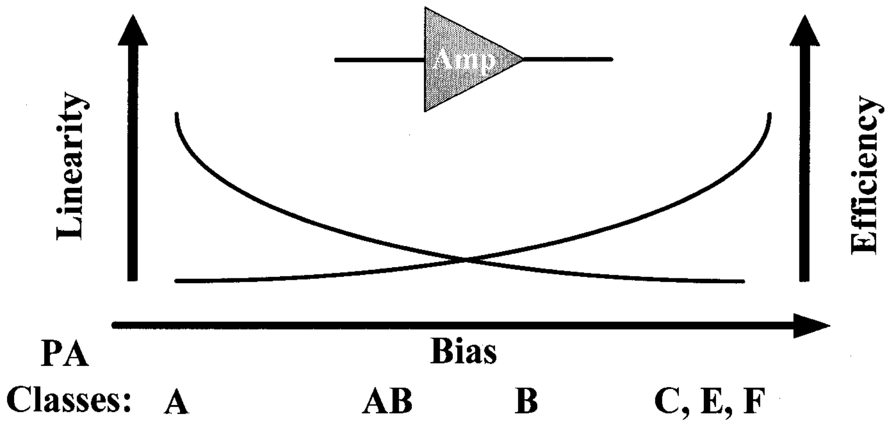


Figure 2-13: Linearity and Efficiency relation for different PA classes.

Hence, based on the previous discussion and due to the practical requirements, efficiency can be defined as follows: power efficiency (PE) or drain efficiency (η) which can be defined as the ratio of RF-output power to dc-input power, as given by equation (5):

$$PE = \eta = P_{RF_{out}} / p_{DC} \tag{5}$$

This measure may be enough for low frequency voltage-to-voltage conversion amplifiers. But since high frequency RF current-to-voltage or current-to-current amplifications are necessary due to matching limitation, it is important to add the loss in the amplifier in the equation, so that other efficiency metrics like the power added efficiency can be considered. The Power added efficiency (PAE) is calculated as the ratio of the RF output power, minus the input RF power, to the total power into the device (DC and RF), as stated in equation (6) [10].

$$P_{AE} = (P_{RF_{out}} - P_{in}) / p_{DC} \tag{6}$$

Thus, the PAE includes the RF-drive power by subtracting it from the output power. The PAE gives a good indication for the PA performance when the gain is high. An example of power added efficiency curve as a function of input power was shown in Figure 2-12.

In addition, the overall efficiency (η_{All}) can be used in all situations. It can be defined as shown in equation (7). In this context, it is important to mention that this definition could be extended to include any other sources of power consumption like driver dc-input power or the power consumed by supporting circuits.

$$\eta_{All} = p_{RFout} / (P_{in} + P_{DC}) \tag{7}$$

Another important efficiency metric is the instantaneous efficiency, which is the efficiency at one specific output level. For most PAs, the instantaneous efficiency is at the highest level at the peak output power (P_{peak}) and would decrease as the output decreases. The average efficiency is a useful measure of performance when amplifying signals with time-varying amplitudes are involved. It is calculated as the ratio of the average output power to the average dc-input power as expressed in equation (8).

$$\eta_{Avg} = p_{RFoutAvg} / P_{DCAvg} \tag{8}$$

Besides, the probability-density function (PDF) presents the relative amount of time spent by the signal's envelope at various amplitudes. Modulated signals with multiple carriers produce random- phasor sums and thus have Rayleigh-distributed envelopes as it can be seen in Figure 2-14. By integrating the product of the variable of interest and the PDF of the envelope over the range of the envelope, the average input and output powers are found.

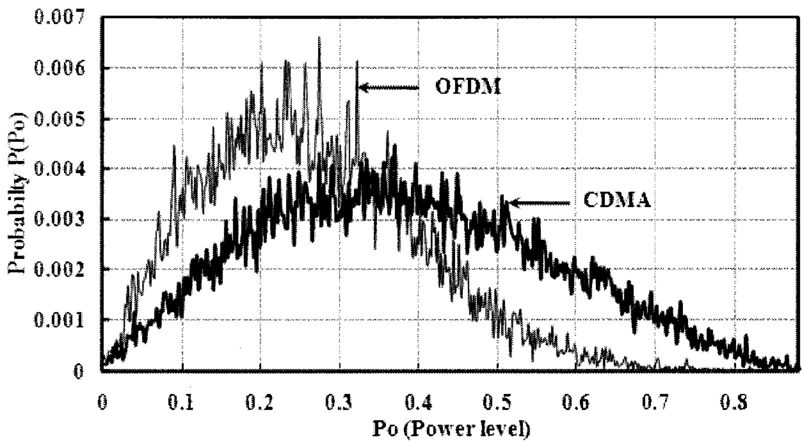


Figure 2-14: Probability Density Function for OFDM and CDMA signals.

2.4 Conclusion

In this chapter an overview of the wireless communication was introduced, and new trends in the field were presented. The different modulated signals were presented along with a description of the main characteristics concerning their channel allocation, bandwidth efficiency, and their number of user's capacity. Then, the OFDM technique was briefly highlighted upon for its importance and hence practicality for the use in wireless systems. The assessment of the performance of the communication system is also presented with a discussion about the linearity and efficiency concerns. The linearity as one of the main concerns in the design of modern PAs for use in wireless communication applications is discussed. In addition, the need for efficiency improvement as a critical factor in RF and microwave power amplifiers design is presented. Different parameters, used to measure the linearity and efficiency, were introduced.

CHAPTER 3

POWER AMPLIFIERS AND TRANSMITTERS

3.1 Introduction

A power amplifier (PA), in a simple definition, is a circuit for converting DC-input power into a significant amount of RF/microwave output power. Typical architectures employ large PAs to amplify a low-level signal to the desired output power. However, a wide variety of architectures have been proposed, which basically disassemble and then reassemble the signal to permit amplification with high efficiency and linearity [10]. The simplest way to design a power amplifier is to design a single power-amplifier gain stage using a single transistor. However, any practical power amplification architecture consists of several drivers, gain stages, and a final power stage which may use some form of power combining network. Generally, transmitters do not only use PAs as building blocks, but also a variety of other circuit elements including oscillators, mixers, low-power amplifiers, filters, matching networks, combiners and circulators. The arrangement of building blocks is known as the architecture of the transmitter. The classic PA transmitter is based on linear PAs and power combiners. But lately, the PA transmitters are being based on a variety of different architectures as reported in [1],[12] [10], [43] and [48].

Meanwhile, new solid-state devices such as HEMT, pHEMT, HFET and HBT, which are developed using a variety of materials such as GaAs, InP, SiC and GaN emerged in the 90s, these new devices offer amplification up to 100 GHz or more. PA based transmitters are used in systems such as radars, RF heating, plasma generation, laser drivers, magnetic-resonance imaging and miniature DC/DC converters. No single PA or transmitter architecture suits all the applications. Most of the PA architectures that are now coming into the market, were created decades ago, but just made possible recently, thanks to the progress in signal-processing and control technology.

The combination of digital signal processing and microprocessor control allows widespread use of complicated feedback and predistortion techniques to improve the PA's efficiency and linearity as reported in [51][50] and [50], Modern applications, like communication, navigation and broadcasting systems, operate in different range of frequencies starting from UHF to millimeter frequencies. PA output power ranges from 10 mW in short-range unlicensed wireless systems to 1 MW in long-range broadcast transmitters. In addition, almost every possible type of modulation is being used in any system.

Power amplifiers are used in many different applications including the majority of wireless and radio communication equipments, wireless and cable TV broadcast systems, cable and other wired transmission systems, optical driver amplifiers, audio systems and radars. Over many years, the knowledge of related technologies and the design of these amplifiers have been developed. In this context, Table 3-1 represents some interesting statistics based on the number of IEEE publications indexed under "Power Amplifier". While some knowledge has been developed that is common to a wide variety of applications, increasing specialization has led to an important advance in technology for specific applications.

Table 3-1: Published articles indexed under "Power Amplifiers" in IEEE and affiliated publications.

Publication Year	*Before 1980*	*1980 to 1990*	*1990 to 1998*	*1998 to 2007*
Number of Articles	195	397	1682	1854

3.2 Power efficiency enhancement techniques

A conventional power amplifier is designed to provide maximum efficiency at a single power level, which is customarily near the saturation power level of the device [12]. When the PA operation point is backed off, the efficiency degrades sharply and the heat dissipation increases, even if the RF output power decreases. This problem is unavoidable, if the amplitude modulation of the RF envelope varies between peak and minimum values.

Effective solutions for this problem have existed since long time, and they are known as “efficiency enhancement techniques”. The three main classical efficiency enhancement techniques are [10]: Doherty amplifier, LINC (outphasing) amplifier and Kahn envelope elimination and restoration technique. These three techniques have potential widespread applications in wireless communication systems. Also, their implementation with ease and effectiveness benefiting from the expanding digital technologies is assessed. Some new techniques are introduced in [13], [14], [22] and [49].

A circuit level solution was introduced in [34]. It is a new load modulation technique in which the load impedance of the PA is dynamically varied to produce amplitude modulated signals with high efficiency for narrowband signals, but it needs design efforts for the modulator biasing and electronic tuning networks to achieve high-efficiency and linear amplification in wideband applications. A device level design was also presented in [14]. It is based on a design of a class F power amplifier for efficiency enhancement. Besides, a device/circuit category design for efficiency was introduced in [13]. This design offers good efficiency results, but the cost was relatively high due to the use of four amplifiers, among which one should be active for low amplitude envelope signal. In addition, when large amplitude signals are applied, the four PAs should be active. This can be obtained with a specific design of a dual mode input power divider and an output power combiner.

Besides, there were different research activities to design and implement LINC architecture, but all of them were based on the architecture mentioned before. Research work presented in [21][38], [40] and [51] focused on increasing the LINC immunity against the branch imbalances, and thus improving the efficiency.

3.2.1 Conventional Power Amplifiers

Conventional linear transmitter architecture is a simple line up of the typical microwave PA components. As shown in Figure 3-1, this transmitter line up consists of a baseband or IF modulator, an up-converter and a power-amplifier chain.

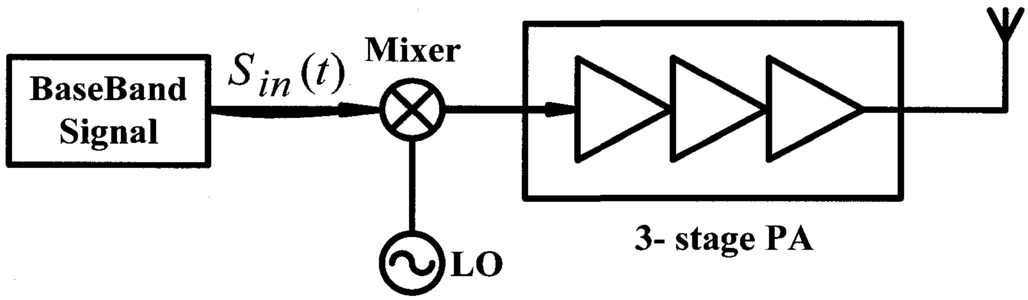


Figure 3-1: Linear PA architecture.

The cascaded amplifier chain consists of gain stages with power gains in the range of 6–20 dB. Each stage must have adequate linearity, if the transmitter is intended to produce an amplitude-modulated or multicarrier signal. This is achieved generally using class-A amplifiers with substantial power back-off in all driver stages. The final amplifier (output stage) is preferably operated in class AB, as it is always the most costly in terms of device size and current consumption. Despite of the lower efficiency, it is necessary to use class-A PA in applications requiring very high linearity [12].

3.2.2 Power combining

The use of a single large PA versus a number of small PAs is one of the most basic decisions in the selection of the PA architecture. Even when larger devices are available, smaller devices often offer higher gain, a better matching factor (wider bandwidth), better phase linearity and better cost. Heat dissipation is more readily accomplished with a number of small devices. On the other hand, the increase in part's count, assembly time and physical size are significant disadvantages to the use of multiple, smaller devices. In Figure 3-1, a multi-way power combiner/divider is shown. It is a 2-level one-to-four using a simple 3dB hybrid power combiner/divider [9], [10] and [12].

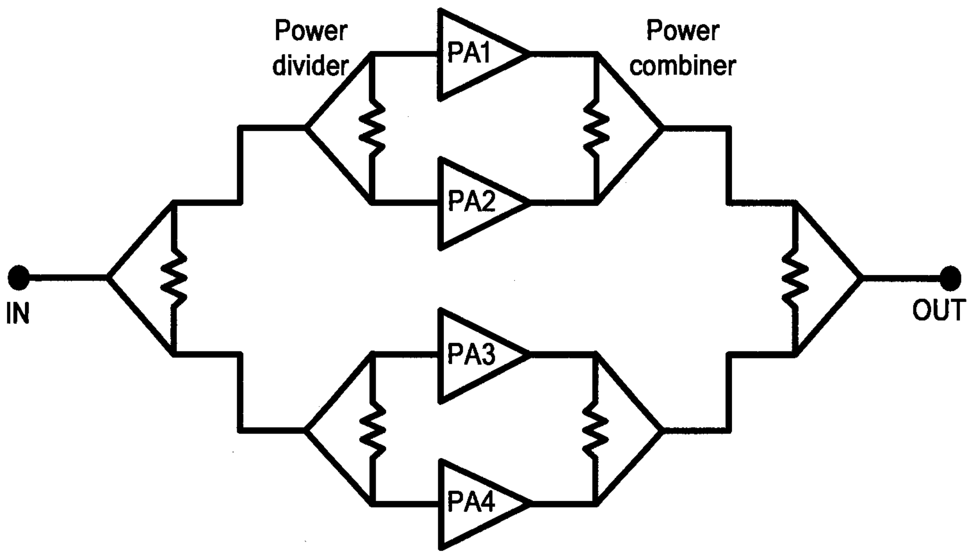


Figure 3-2: Multi-way power combining using a simple 3dB hybrid.

3.2.3 Stage bypassing and gate switching

By switching between large and small amplifiers (e.g., the driver), the stage-bypassing and gate-switching techniques reduce power consumption and increase the efficiency according to peak signal level. The transmitter efficiency could be significantly increased when operating into the backoff. The adoption of these techniques is particularly effective for mobile handsets that operate over a large dynamic range. Meanwhile an average efficiency improvement from 2.1% to 9.5% has been reported. Also, the efficiency vs. output for different PA architectures in continuous wave mode is illustrated in [10].

3.2.4 Envelope elimination and restoration (EER), (Kahn) technique

In the Kahn envelope elimination and restoration (EER) technique, shown in Figure 3-3, a high-efficiency linear RF PA is implemented by combining a highly efficient but nonlinear RF PA with a highly efficient envelope amplifier. In the typical implementation of this technique, a limiter eliminates the envelope and thus generates a constant-amplitude phase modulated carrier to be amplified efficiently by class-C, class-D, class-E, or class-F RF PAs. The envelope is restored to the phase-modulated carrier by amplitude modulation using the final RF PA. This results in the creation of an amplified replica of the input signal.

Kahn-technique based transmitter operates with high efficiency over a wide dynamic range in contrast to linear amplifiers. It produces high average efficiency for a wide range of signals and power backoff levels. Three to five times the average efficiency of linear amplifiers has been obtained from HF to L-band using the Khan technique [10] , [12]. The most important factors affecting the linearity are the envelope bandwidth and the alignment of the envelope and phase modulations. The envelope bandwidth must be at least twice the RF bandwidth and the misalignment must not exceed one-tenth of the inverse of the RF bandwidth [10]. Also, at higher microwave frequencies, RF-power devices exhibit softer saturation characteristics and larger amounts of amplitude-to-phase conversion, necessitating the use of predistortion.

Besides, it should be mentioned that there is an architecture called "Envelope Tracking" which is similar to the Kahn technique. In this architecture, the supply voltage is varied dynamically to conserve power, but with sufficient "headroom" to maintain the RF PA operation in the linear mode. The final RF PA carries out the task of providing the linear amplification. The envelope is first detected and used to control a dc–dc converter. Architecture's efficiency is significantly better than that of a linear RF PA operating with a fixed supply voltage, but it is still lower than that of the Kahn technique as stated in [10]. The reason for that is, at lower output amplitudes, power consumption by the converter and other circuits reduces the efficiency.

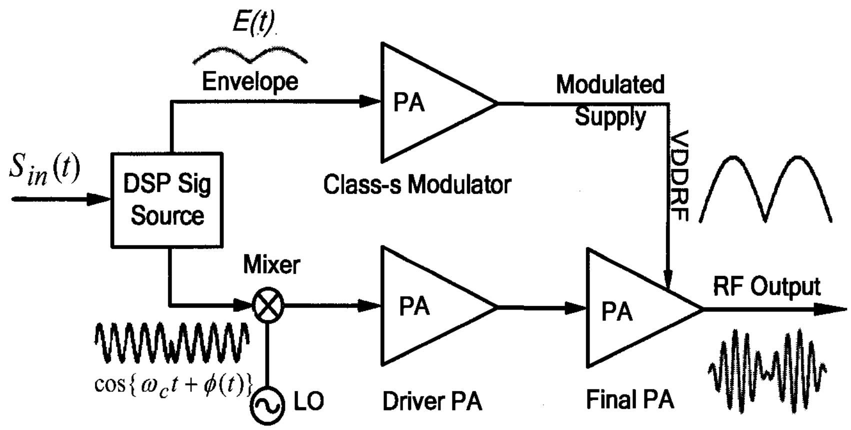


Figure 3-3: Kahn-Technique PA architecture.

3.2.5 LInear Amplification Using Nonlinear Components (LINC):

This architecture came into use at microwave frequencies in the 70s. It originated from an older technique called *outphasing,* which was invented by Chireix as a mean of obtaining high-quality AM modulated signal from vacuum tubes with poor linearity, [11], [17]. In the Chireix technique, shunt reactances are used in the combiner inputs to tune out the drain reactance at particular amplitude as shown in Figure 3-3. This in- turn, maximizes the efficiency in the vicinity of that amplitude.

The efficiency is maximized, in the classic implementation, at the level of the non modulated AM carrier and remains high over the upper 6 dB of the output range and for about 8 dB into backoff [10]. The average efficiency can be maximized for any given signal by carefully choosing the shunt susceptance values. For example, for a multicarrier signal having 10-dB peak-to-average ratio, the average efficiency can be boosted from 28% to 52.1% for class B PA [10], [11], [17] and [42].

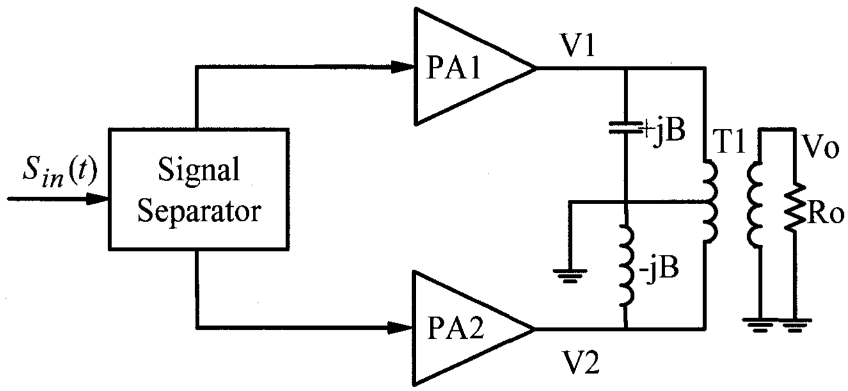


Figure 3-4: LINC PA architecture.

The LINC is considered as a potential architecture level solution for efficient RF power amplification systems. The LINC amplifier architecture is intended for applications in which the transmitted signals should have high output power level and high efficiency, while maintaining good linearity. The LINC concept is based on converting the complex amplitude modulated signal into two-constant amplitude out-phase modulated signals. The LINC architecture basically consists of a signal separation block and two nonlinear amplification branches, followed by a combiner.

The LINC architecture permits a power amplifier operation near or at saturation level so that the two separated signals yield maximum amplifier efficiency and high linearity. Hence, this architecture provides high efficiency and secures good linearity [11], [15], [16], [52] and [22]. Consequently, the utilization of LINC amplifier architecture in systems employing complex modulation and multiple access technologies (e.g. OFDM, WCDMA, QAM, etc.) comes in place. However, degradation of the average efficiency due to the power loss in the LINC combiner is a major problem. This problem is worse when the LINC is utilized to amplify signals having high PAPR by using a hybrid combiner which is a matched and lossy combining device [54]. However, If a lossless matched combiner (Chireix combiner) is utilized, the linearity is degraded [15], [20] and [55].

3.2.6 The Doherty Amplifier

The Doherty architecture in its classical form combines two equal power PAs through quarter-wavelength lines or networks. The "carrier" or main PA is biased in class B, while the "peak" or auxiliary PA is biased in class C. When the signal amplitude is half or less than half of the P_{peak} amplitude, the carrier PA is active. The two PAs would contribute to the output power, when the signal amplitude is larger than half of the P_{peak} amplitude. A simple layout of the Doherty amplifier is shown in Figure 3-5.

The Doherty amplifier operation can be understood by dividing it into three regions: 1) low-power region, 2) medium-power region (or load-modulation region) and 3) peak-power region.

In the low-power region, the peak PA remains in cut-off and appears as an open circuit. Hence, the carrier PA would operate as an ordinary class-B amplifier, as it sees a 100 ohm load. The instantaneous efficiency increases with the output power, reaching 78.5% in the ideal class B PA at saturation and at -6 dB OPBO from PA transmitter P_{peak}. The peak PA becomes active as the signal amplitude increases to the medium-power region. The apparent load impedance to the carrier PA decreases from 100 ohm to above the 50 ohm during medium power range and the load seen by the peak PA decreases from infinity to 50 ohm. The load presented to the carrier PA is decreased by the transformation through the quarter-wavelength line. Meanwhile, the carrier PA remains in saturation acting as a voltage source. It operates at peak efficiency and delivers an increasing amount of power. Both PAs see 50 ohm loads and each PA delivers half of the system output power at P_{peak} power region.

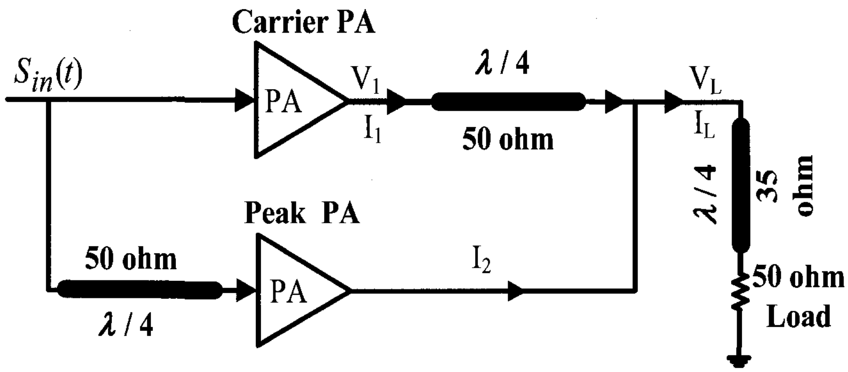


Figure 3-5: The Doherty amplifier architecture.

DSP is used in recent realizations in order to control the drive and bias of the two PAs. This results in more precise control and higher linearity [56]. Besides, an average efficiency of nearly twice that of a quadrature-combined PA is exhibited by *S*-band Doherty LDMOS transmitters with the same ACPR [13]. Three or more stages are also possible to be used to keep the instantaneous efficiency relatively high over a larger back-off range. A three stage Doherty with ideal class-B PAs delivers an average efficiency of 70%, for a Rayleigh-envelope signal type with 10-dB peak-to-average ratio [57].

3.3 Conclusion

In this chapter, a review of the efficiency enhancement techniques was presented. Also a survey for the most used technologies and topologies was presented. Power enhancement techniques like power combining, stage bypassing, LINC, and Doherty are presented. The concepts behind these techniques have been explained along with a discussion of their performance in terms of efficiency and linearity.

CHAPTER 4

DESIGN AND OPTIMIZATION OF LINC TRANSMITTER FOR OFDM APPLICATIONS

4.1 Introduction

Radio transmitters with high linearity and high power efficiency will be required for future mobile communications systems. Several linearization techniques for power amplifiers have been proposed including Feedforward, Feedback, Pre-distortion, CALLIUM transmitters and LINC architecture. Among these techniques, LINC is considered as one of the most promising schemes as it does not use the feedback loop and thereby insures the circuit stability. The theoretical peak efficiency of the LINC system has been reported in [11] to be 100%, since highly efficient nonlinear power amplifiers operating in class-E or class-F modes can be used.

The LINC is selected in this work to implement a system level power amplification technique for OFDM applications, and applicable for other standards. The LINC concept is introduced and the signal decomposition is presented. Also, the combiner's effect on the LINC power efficiency performance is introduced. The optimization of the LINC through the introduction of an additional filtering stage in the LINC's PA branches to fit the signals within the IEEE standard transmission mask is discussed. The regular LINC is presented, and then the digital implementation of the LINC power amplifier is presented.

4.2 LINC concept

In LINC architecture, power amplification is based on the vector summing of two constant-amplitude phase-modulated signals [11]. A simple layout of a LINC transmitter is shown in Figure 4-1. The phase modulation forces the instantaneous vector sum of the two PA outputs to follow the desired signal amplitude. The driving signals are phase modulated inversely proportional to the cosine of the envelope *(E)* of the input signal.

However, the LINC technology has some problems in circuitry and due to the component's mismatch between the two branches (imbalance) causing signal degradation. Additional problems are related to the efficiency of the signal splitter and power dissipation in the combiner.

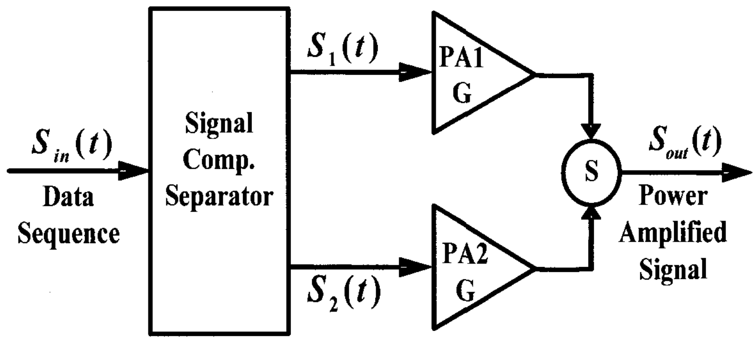


Figure 4-1: Regular LINC amplifier architecture.

The design and power efficiency issues of the LINC combiner were discussed in [11], [15] and [58] . The hybrid combiners are employed to ensure the isolation between the two PAs, and allow them to "see" resistive loads at all signal levels [15], [18], [52] and [52]. The efficiency of a LINC transmitter using a hybrid-coupler, results in an average efficiency that is inversely proportional to signal peak-to-average ratio [15]. Some improvements in the efficiency are offered by power recovery from the dump port of the hybrid combiner.[59], [60].

The variable reactive PA-load impedances resulting from summing the out-of-phase signals in a non hybrid combiner degrades the linearity due to impedance mismatch seen by the amplifiers in the two branches [52]. A new approach for the analysis of the outphasing combiner was presented in [15]. Also, a comprehensive review of the combiner design and efficiency issues was reported. Furthermore, the effect of modulation scheme on the combiner efficiency and consequently on the overall LINC power efficiency was studied. Besides, a new integrated wideband CMOS RF combiner for wireless LINC transmitters was introduced in [61], and a CMOS LINC was implemented for OFDM systems that have digital phase modulation capable of compensating for the mismatch effects was introduced in [62]. Also, a novel integrated antenna design was presented in [63] -[67] to carry out the function of the two-branch signal combiner and the transmission antenna, and thus boosting the efficiency by removing the combiner loss as claimed by the authors. In addition LINC amplifier was used to build SDR transmitters [81]. The travelling wave tubes amplifiers were used to construct a LINC transmitter for high power range [82].

Signal splitting was the focus of many research studies aiming at designing a trouble-free splitter without causing any signal distortion and imbalance [69]. A recent research work presented a DSP and a synthesizer as a digital signal splitter (separator) implemented for W-CDMA signals [68] . Meanwhile, the problem of branch mismatch was tackled in [21], [38], [72], [72] and [73][45]. A solution was proposed using pre-distortion techniques as described in [50], [50], [21] and [74]. A good survey on the imbalance minimization technique was presented in [70] and two complex algorithms were introduced to correct the imbalance. Also, [38] presented a digital compensation solution for the imbalance resulting from the signal separator for OFDM applications. Besides, in [45] a novel full-digital baseband method was introduced. It corrected for both gain and phase imbalances in LINC. However, this solution was only considered for amplifiers having memory-less models. A closed form expression was used detect and compensate for the mismatch in LINC system, in [59]. In this method, the phase and magnitude mismatches are measured accurately and could be corrected for and good results are presented.

Other researches focused on the RF analog implementation of the LINC architecture [11], [23], [31] and [76]. The digital implantation trials for LINC imbalance compensation and predistorted LINC are found in [34], [38] and [92]. The use of the genetic algorithms to overcome the imbalance effects is presented in [77]. Finally, some research works have proposed to modify the LINC architecture or to combine it with other topologies to produce a new amplifying architecture with improved properties like the ELINC (Enhanced Linear Amplification with Non-linear Component) [71], Mode-Multiplexing LINC Architecture [40], CLIER (Combination of LINC and EER method) [49] MILC (Modified Implementation of the LINC Concept) [78] and Multilevel LINC System [79], [80]. In addition, [84], presents a new topology for the LINC, which is based on a new quadrature outphasing, improving the transmission power.

4.2.1 Regular LINC 1X1 architecture:

As argued before, LINC amplifiers are proposed for applications in which the transmitters should have high output power and high efficiency with the required linearity of the application. However, LINC is inherited with some problems in its circuitries like components mismatch between the two branches. Also, it suffers from power efficiency degradation due to the signal recombination after amplification using the power combiner.

The LINC amplifier consists of a signal component separation block (SCS) that divides the baseband signal into two constant amplitude and phase-modulated signals. The two signals are up-converted to the RF signal around the carrier frequency and amplified afterwards. They are summed by a power combiner to reconstruct an amplified, undistorted and modulated RF signal, as shown in Figure 4-1.

Branch signals generation involves generating two signals: a narrow band one and a wideband signal that extends into adjacent channels. When the two signal components are recombined, the two source signals are added in-phase, while the wideband signals cancel each other. This is true under the assumption that there is no phase or gain imbalance in the two branches. If there is imbalance, the cancellation will not be complete and the adjacent channels will be affected. Therefore, the combination process requires more attention. Since the envelope of both branch signals is constant in magnitude, LINC permits the RF power amplifiers to operate near saturation thereby yielding, in principles, maximum power efficiency [3].

4.3 LINC signal decomposition

While the efficiency of microwave power amplifiers is one of the most critical elements in overall communication system power dissipation, and most approaches to improve amplifier efficiency result in a loss of linearity. That is unacceptable for communication systems employing advanced and spectrally efficient modulation techniques. That would be the case for modulated signals such as OFDM and CDMA, as stated in the previous chapters. Since the main disadvantage of OFDM is that the signal peak may rise up to 50 times the average power, it will force transmitter amplifier to operate, during part of the time, in its nonlinear region. As a result inter-modulation distortions will be generated and thereby increasing the BER [14], [15]. Hence, the application of LINC architecture for amplifying such modulated signals will be the choice to tackle this issue in this study.

4.3.1 The amplified Output signal

At the output of the nonlinear PA, the complex envelope model for such band pass nonlinearity signal, is given by equation (1)

$$S_{out}(t) = A(R)e^{j(\theta(R)+\arg(S_{in}(t)))} \tag{1}$$

where $S_{in}(t)$ is the complex envelope at the input. A(R) and θ(R) denote the AM-AM & AM-PM conversion functions for an input envelope $R = |S_{in}(t)|$.

4.3.2 Signal decomposition

If a band pass signal with complex envelope S (t) is used and if $|S(t)| \leq S_M$ then S (t) can be written as:

$$S_{in}(t) = S_1(t) + S_2(t) \tag{2}$$

where

$$S_1(t) = S_{in}(t) / 2 + e(t) \tag{3}$$

$$S_2(t) = S_{in}(t) / 2 - e(t) \tag{4}$$

$$e(t) = \frac{j}{2} S_{in}(t) \sqrt{\frac{S_M^2}{\left|S_{in}(t)\right|^2} - 1} \tag{5}$$

where S_M is the maximum amplitude of the signal.

Also, there is another method to perform the two branch amplification in LINC technique. The sent signal is assumed to be a slight replica of the input signal. This means that the output has a complex envelope given by $G\,S$(t), where G is the complex gain factor as shown in Figure 4-1. Due to the possible phase and gain imbalances between the two amplifiers the output complex envelope would be written as:

$$S_{out}(t) = G_1 S_1(t) + G_2 S_2(t) \tag{6}$$

where G_1 and G_2 are two complex constants, possibly different.

The two-branch amplification (LINC technique) signal decomposition can be presented in another form based on the baseband modulated signal having complex envelope. As, the input signal $S_{in}(t)$ can be decomposed into two constant envelopes out- phased modulated signals $S_1(t)$ and $S_2(t)$, as shown in Figure 4-2.

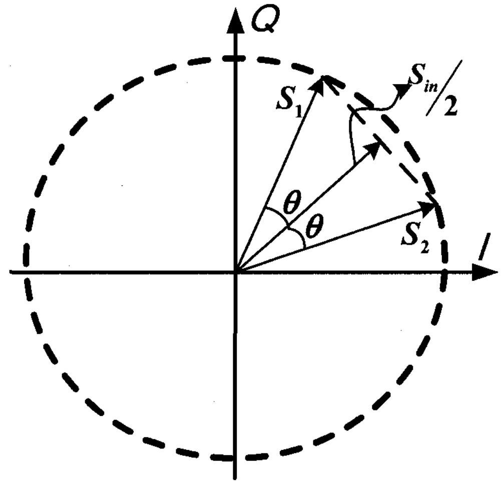


Figure 4-2: LINC amplifier signal decomposition.

The relations between the signals are given as follows:

$$S_{in}(t) = r(t).e^{j.\varphi(t)} = s_1(t) + s_2(t) \tag{7}$$

$$r(t) = r_{\max}.\cos(\theta(t)) \tag{8}$$

$$s_1(t) = \frac{r_{\max}}{2}.e^{j(\varphi(t)+\theta(t))} \tag{9}$$

$$s_2(t) = \frac{r_{\max}}{2}.e^{j(\varphi(t)-\theta(t))} \tag{10}$$

where r_{max} is the input signal's envelope at saturation level. The output signal, assumed to be a replica of the input signal, is expressed as follows:

$$S_{out}(t) = G(S(t)) = G(s_1(t) + s_2(t)) \tag{11}$$

where G is a complex gain of the amplification stage. This gain can be different for the two-branch amplifiers due to the possible phase and gain imbalance problems. This system was simulated using ADS as shown in appendix B, Figure B-1.

4.4 LINC efficiency and combiner technologies

The average efficiency of LINC amplifier depends on the signal's dynamic and the combiner's efficiency [85]. The two types of combiners commonly used are: the matched power combiner and the Chireix outphasing combiner [86], [87]. The isolated two-way (hybrid) power combiner results in an excellent linearity, but in the same time degrades the overall power efficiency of the LINC system [15].

In-fact, the Chireix outphasing combiner is a lossless combiner that improves the power efficiency, but degrades the linearity of the LINC system. It has been shown that the distortion observed in the LINC amplifier with a Chireix-outphasing combiner is inherent to the combining structure itself [20]. In spite the fact that there ongoing efforts to overcome this problem introduced in [88], [89] and [90]. But, when considering the hybrid combiner, it had been shown that the only source of linearity degradation is the phase and/or amplitude imbalance between the two LINC branches [15] , [54]. The third source of linearity degradation is the band pass filters used in the transmission chain between the LINC separator circuit and the RF amplifiers.

The power efficiency of the LINC transmitter can be computed using the following formula:

$$\eta = \eta_a \eta_b \eta_c \tag{12}$$

where η_a is the peak amplifier's efficiency, η_b is the ratio between the average transmitted power and the intended peak power at the transmitter output (it also corresponds to the efficiency of the signal recombining process), and η_c represents the loss in the combiner itself [54].

The instantaneous combiner efficiency for the matched, isolated combiner can be computed analytically, to be found equals to the function of cos2 (θ), where θ is the decomposition angle. The efficiency increases as θ decreases. This corresponds to signal peaks as illustrated in Figure 4-4. Also, as illustrated in Figure 4-4, the efficiency decreases as θ increases, which corresponds to low signal level. This is the most probable case for the signals used in 3G and 4G communication systems as shown in Figure 4-3.

The average efficiency computed for the matched combiner for the case of OFDM signal is about 29% [54]. In most cases, when the input signal amplitude is small compared to the constant amplitude of the two components generated from it, the combiner have to dissipate a huge amount of power to be able to reconstruct the signal and generate the small amplitude signal after amplification. This obviously degrades the power efficiency for the LINC technique.

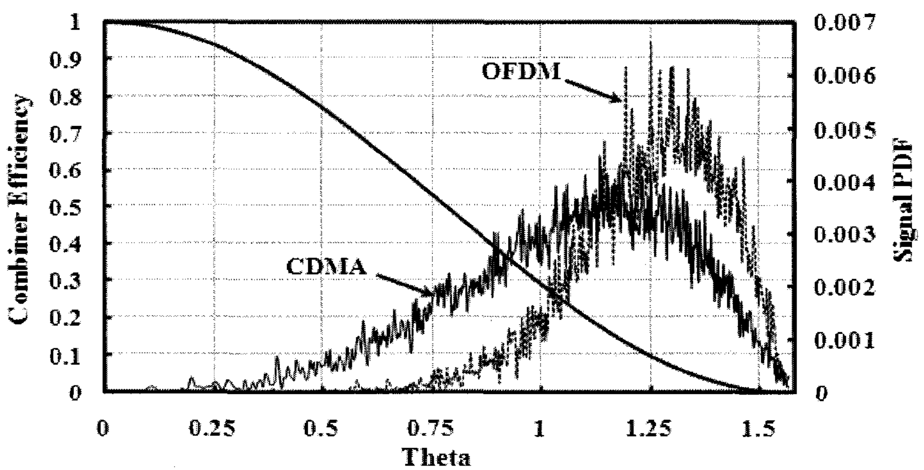


Figure 4-3: Matched combiner efficiency and PDF for OFDM and CDMA modulated signals vs. decomposition angle Theta (θ).

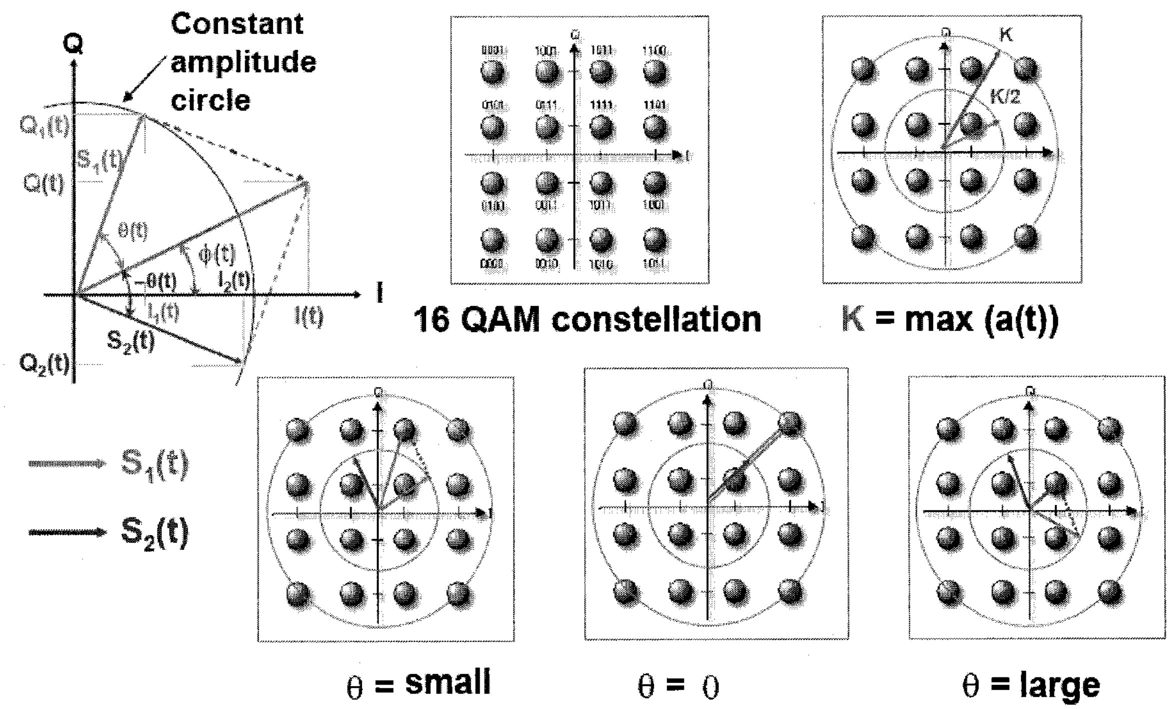


Figure 4-4: LINC amplifier signal decomposition showing different (θ) values [54].

4.5 Design optimization of LINC system

As presented before, the main drawback of the LINC technique was the efficiency degradation due to the signal splitter, the signal combiner and the imbalance between the two combiner paths. The imbalance between the two branches of the LINC is a very delicate issue too, as it is almost impossible to get fully balanced LINC architecture due to practical issues like getting two identical amplifiers

Since OFDM is widely used in recent wireless applications, it has been studied intensively lately [8]. The use of OFDM scheme for data modulation in WLAN applications helps incorporating high data rates, and solves the fading problem for indoor and time dispersive channels.

However, OFDM signals show strong envelope fluctuation, which is considered as a real critical design issue. The high PAPR would require using large size power amplifier with high linearity performance, which would operate in high input back-offs, thereby reducing the power efficiency and the dynamic range. A number of digital signal processing approaches were proposed to reduce the PAPR of the OFDM modulated signals. These schemes offer considerable reduction of the PAPR and improve the power efficiency [8]. However, these schemes impose heavy computational challenges for systems using large number of sub-carriers. For that reason, the use of the LINC technique was proposed for OFDM based systems [1], [45][72], [50] and [72]. The measurement of LINC performance, when OFDM signal is used, have not been widely reported or discussed [7], [72]. In what follows, a modified LINC architecture will be proposed. It is based on filtering the branch signals, which results in reducing the out-of-band signal emissions, hence improving the ACPR and increasing the system tolerance to imbalances.

4.5.1 LINC branch signals Filtering

It should be noted here that digital filters are used to shape the branch signals and fit them within the IEE 802.11g transmission spectral mask in the proposed LINC system. However, to filter the modulated signals for such applications, the most important requirement for the used digital filter is to have linear phase distortion. Generally FIR (Finite Impulse Response) filters are used in applications, where there is a need for a linear-phase filtering. An FIR filter is applied to the *I* and *Q* components of each branch signal.

In addition, taking into account that the signals to be filtered are modulated signals, the FIR filter should meet the following criteria:

- Its phase response in the pass band should be linear.
- Its amplitude attenuation in the pass band should be as low as possible.

- It should have sharp cut off frequency (to minimize out of band emissions).
- Its attenuation in the stop band should be high (to improve ACPR).

4.5.2 Filter design for regular LINC architecture

This section introduces filters adaptation to shape the LINC branch signals. The branch signals are filtered (after decomposition and before being up-converted), amplified and then combined as depicted in Figure 4-5. The transmitter contains a DSP block and a Tx RF front end. The DSP block contains the Signal Component Separator (SCS) and the shaping filters to reduce out-of-band emissions while at the same time improve the resulting combined signal ACPR. Meanwhile, the power efficiency is maintained and the value of EVM is kept within the standard limits.

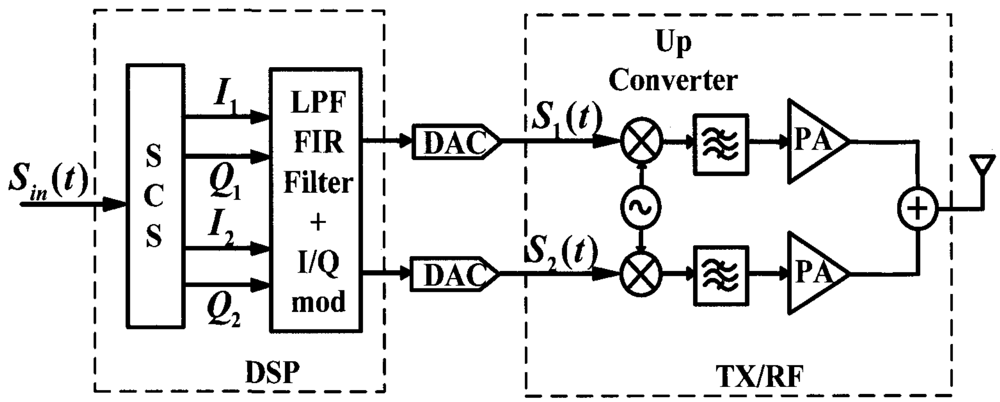


Figure 4-5: New LINC transmitter including FIR LPF block.

The SCS decomposes the baseband signal $S_{in}(t)$ into the two constant amplitude signals, $S_1(t)$ and $S_2(t)$ and calculates their rectangular representation (I_1,Q_1) and (I_2,Q_2), respectively. Meanwhile, digital filters are used to filter these signals. Filtering the branch signals of the LINC architecture introduces dynamics in the signal (the peak-to-average power ratio increases from 0.0 dB to approximately 3.0 dB) forcing the use of linearization for the amplifiers, as they are working near saturation and over 3 dB dynamic range [91], [92]. The resulting IF signals are then converted to analog using digital-to-analog converters (DACs). In the RF front end, the IF signals are upconverted, amplified, combined and then fed to the input port of the transmission antennas.

The used filters were digital FIR lowpass filters, of the order 60. The four types of filters studied were least square, equiripple, window (Kaiser) and raised cosine. The pass band frequency for the least square and equiripple filters was 9.5 MHz, and the stop frequency was 10 MHz; while the cut-off frequencies for the raised cosine and window (Kaiser) filters were 9.25 MHz and 9.5 MHz, respectively. The filter synthesis was performed using MATLAB software. The simulations were carried out using Agilent Advanced Design System (ADS). The synthesized filter tabs are presented in appendix A.

Results for regular LINC amplifier are depicted in Figure 4-6 and Figure 4-7. Which show the input and output of branch signals spectrums, drawn with respect to the RF reference carrier frequency of 2.4 GHz. Also, it is shown how the ACPR performance has been improved to comply with the transmission spectrum mask.

In addition, from Table 4-1, it can be seen that the efficiency is about 4.72%, while the EVM is 1.4%. In addition, these results show that this modified architecture has superior performance in terms of ACPR when compared to the regular amplifier-based transmitter system, since this proposed modification (addition of the filter) offers tolerance up to a certain limit to the branch imbalances (mismatch) [47].

Table 4-1: The values of ACPR efficiency and EVM, without and with filtering for regular LINC.

Filter Type	*11MHz*	*20MHz*	*28MHz*	*Efficin.*	*EVM*
Specs	*-20 dBc*	*-28 dBc*	*-40 dBc*		*5.62%*
No Filter	*-26.1dBc*	*-51.1 dBc*	*-56.9 dBc*	*4.72%*	*1.40%*
Least Sq	*-63.8dBc*	*-66.4dBc*	*-66.3dBc*	*4.62%*	*1.41%*
Eq Ripple	*-45.8dBc*	*-63dBc*	*-63.9dBc*	*4.71%*	*1.75%*
Raise Cos	*-52.2dBc*	*-59.1dBc*	*-59.5dBc*	*4.60%*	*1.88%*
Win-Kaiser	*-48.9dBc*	*-61.9dBc*	*-60.7dBc*	*4.64%*	*1.68%*

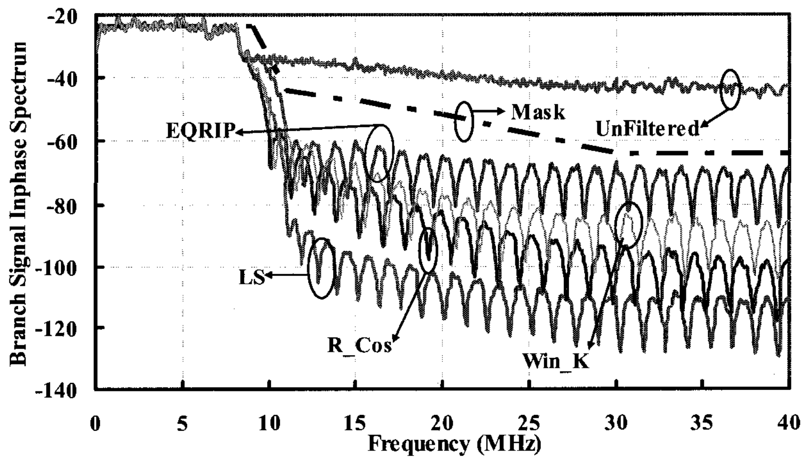


Figure 4-6: Branch signal (In phase) before (unfiltered) and after using filters.

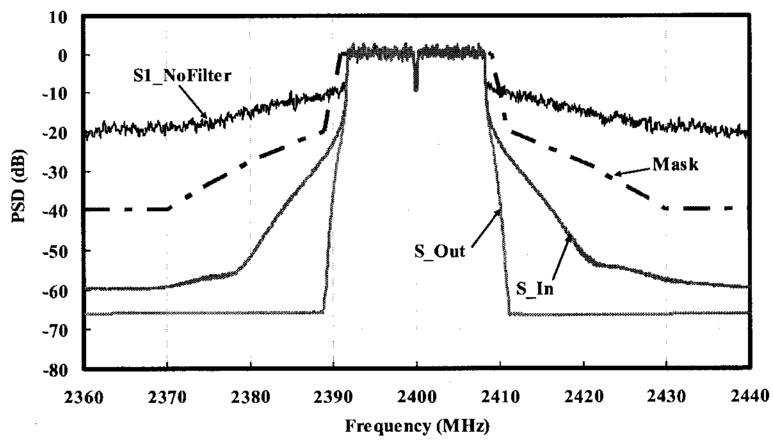


Figure 4-7: Input signal, Branch signal before filter and Transmitted Signal spectrums with respect to mask.

4.6 Mismatch (imbalance) effects

The complex signal imbalance effects between the two LINC branches were studied. The parallel RF branches of the LINC transmitter suffer from unavoidable differences in their magnitudes and phase responses [21]. The effect of this imbalance was corrected using different techniques that are complex to implement. In this study, a modification of the LINC architecture was proposed [47]. This modification was based on applying digital filtering on branch signals. The filters improve the ACPR performance of the system by reducing the out of band parts of the signal and increasing the system's immunity to the branch imbalance, and thus offering a solution with no more overhead on the system. Meanwhile, the power efficiency was maintained and the value of EVM was kept within the standard limits.

Different types of filters were used to study this effect. Simulation results when using the least square filter for different imbalance values between the two branch signals' magnitudes and phases are listed in Table 4-2. The entries of the table show the EVM values. It can be deduced that the ACPR does not change significantly and it is lowered by only 1.3dB in the case when a 3-degree phase and 0.1 magnitude imbalance was considered. In addition, the efficiency is lowered to 4.22%. It should be mentioned that the cases where the EVM exceeds 5.6% are rejected as they don't respect the standard specified limit.

Table 4-2: EVM values when different phase and magnitude imbalances are considered.

Phase/Mag	*0.1*	*0.2*	*0.4*	*0.5*
10	*2.26%*	*3.35%*	*4.5%*	*5.15%*
20	*3.12%*	*3.88%*	*5.13%*	*5.9%*
30	*5.05%*	*5.34%*	*6.35%*	*6.62%*

4.7 Conclusion

This chapter was dedicated to the LINC architecture, the concept of LINC was introduced along with the signal decomposition. Precisely, its main principle was explained and the effects of the signal decomposition on the efficiency were discussed. Then, application of the LINC to amplify the OFDM modulated signals was introduced.

The last part introduced the work concerning the addition of filters in the branches of the LINC amplifier. The filter study was carried out in two stages. It was first applied to the regular LINC in which a new RF power amplifier architecture was implemented. This DSP based architecture performs separation and filtering for WLAN IEEE 802.11g signals. The new architecture is based on a modified LINC amplifier in which the signals in the two LINC branches are filtered to reduce their ACPR and thereby tolerating higher channel interference levels and LINC branch imbalances. The ACPR is improved by 43 dB, when using a least square filter. Meanwhile, the filter action does not affect the system performance in regard to the EVM and the overall power efficiency. In fact, the EVM was almost around that of the case of regular LINC (1.4%) and far less than that of the standard (5.62%).

CHAPTER 5

ADVANCED LINC TRANSMITTER ARCHITECTURES

5.1 Introduction

As pointed out previously, for the LINC architecture, the input envelope-modulated band-pass waveform is decomposed into two constant-amplitude out-phased waveforms which are amplified using highly efficient nonlinear power amplifiers. The outputs are then summed. The LINC advantage is that even though each amplifier is operating in its most efficient mode, the output is still highly linear. However, the main drawback of the LINC technique is the efficiency degradation due to the signal splitter, the imbalance between the two paths, and especially the combiner efficiency issues. Also, the imbalance between the two LINC branches is a very delicate issue. This is because it is almost impossible to get 100% balanced LINC architecture due to practical issues like getting two identical amplifiers. This of course normally leads to distortions in the amplified output signal.

Based on the above discussion, this research work proposes two new system-level solutions to overcome these issues of the LINC architecture by improving the efficiency while meeting the signal linearity requirements. The two proposed architectures are the 2X1 (two transmitting and one receiving antennas) and the 2X2 modified LINC transceiver layouts which are based on the idea of using the receiver antenna(s) to perform the combining process [25], [26][28], [27] and [28][26]. However, the two branch signals to be transmitted are two constant-amplitude signals, which are not compatible with the transmission mask set by the standard. So, to overcome this issue these branch signals have to be filtered beforehand to fit the mask. In what follows, the filtering process will be introduced with application to regular amplifier.

5.2 The 2X1 LINC transmitter system

In this architecture, the branch signals are transmitted, after being filtered to fit the IEEE standard mask for transmission and then amplified. The receiver antenna performs the signal combination as shown in Figure 5-1. The transmitter contains a DSP block and a Tx RF front end. The DSP block contains the SCS and shaping filters. The SCS decomposes the baseband signal, S_{in}(t), into two constant amplitude signals, S_1(t) and S_2(t), and calculates their rectangular representation (I_1,Q_1) and (I_2,Q_2), respectively.

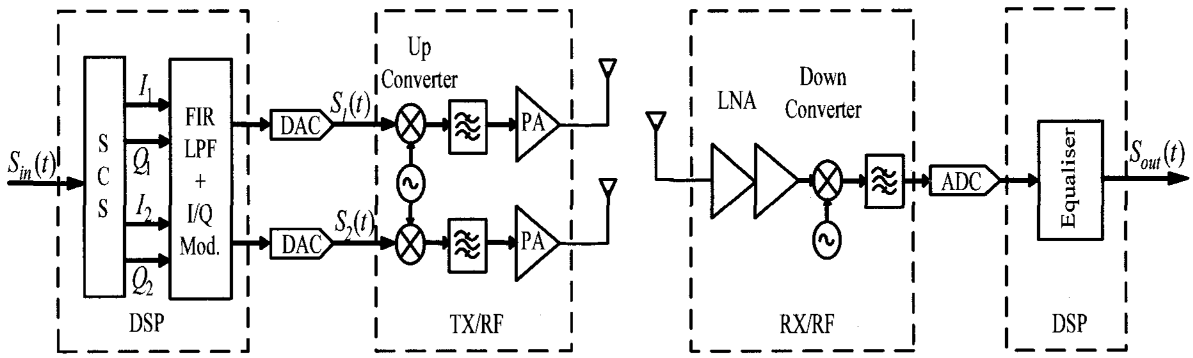


Figure 5-1: Detailed layout of the proposed 2X1 LINC system.

Indeed, the LINC decomposition generates two constant envelope phase-modulated signals. These signals extend into adjacent channels, resulting in an out-of-mask signal violation. Consequently, these signals are not compliant with the standards and cannot be transmitted. Shaping filters, after the LINC decomposition process are therefore required for the proposed architecture to reduce the spectral regrowth of the decomposed signals.

5.2.1 Design optimization and performance evaluation

To implement the new modified LINC architecture, a DSP block is implemented to perform the signal separation process and signal filtering. As the signals in the two LINC branches are filtered to fit the standard spectrum IEEE standard transmission mask and to reduce their ACPR values. In addition, the effect of the imbalance is corrected, in this new implementation, with no extra overhead on the system. The filters utilized, resulted in an improvement in the ACPR performance and the system sensitivity to imbalance effect [27].

It should be noted that the filters used in this part of study were the same filters and are having the same parameters as used in the previous part of study mentioned in chapter 4 [47]. As the filters introduce amplitude modulation (AM) effects in the decomposed signals, the PA linearization is required. So, the DPD (Digital PreDistorsion) was used to linearize the two amplifiers in LINC transmitter as discussed previously. The transmitter's two antennas are placed close enough to each other such that, it can be assumed that both transmitted signals will experience the same channel effect. The equalization algorithms at the receiver would correct for these effects.

The performance of the proposed 2X1 LINC system is evaluated through simulations, using ADS software. The channel model was taken to be a typical office environment channel with Non-line of Site (NLOS) conditions. Indoor Rayleigh multipath fading channel was considered, also additive white Gaussian noise (AWGN) effects were considered. An IEEE 802.11g OFDM signal with a 2.4 GHz center frequency, 20 MHz bandwidth, 64-QAM modulation, 54 Mbps data rate and power of -10.0 dBm was used. The IEEE standard spectrum mask is shown in Figure 5-2. To construct the LINC, the used amplifiers were class AB amplifiers (HMC 408 from Hittite Inc). The small signal gain and the saturated output power of the amplifiers were 20 dB and 32.5 dBm, respectively.

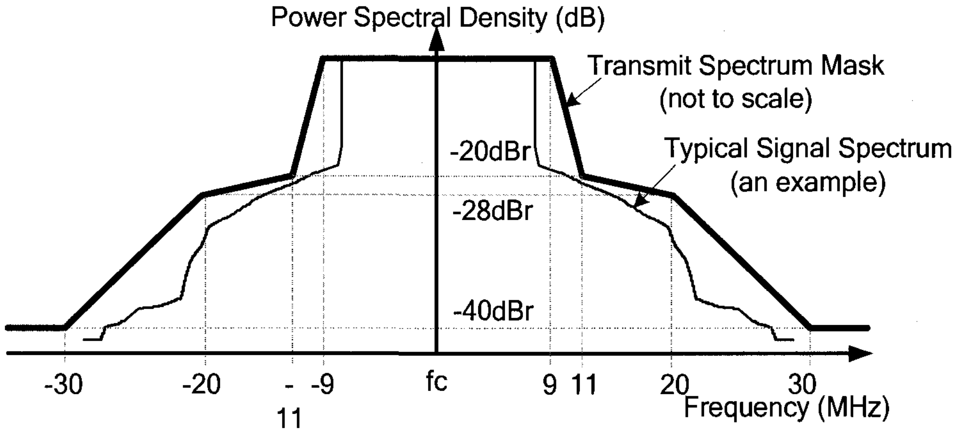


Figure 5-2: Transmit spectrum mask.

The LINC amplifiers AM-AM and AM-PM characteristics and the synthesized AM-AM and AM-PM of the DPD were measured and used in this study as shown in Figure 5-3. The different system components like the combiner were assumed to be ideal. The attenuation in the two LINC paths was assumed to be negligible. The MATLAB software was used to synthesize the filters employed for shaping the branch signals. Digital FIR low pass filters, having an order of 60, were used.

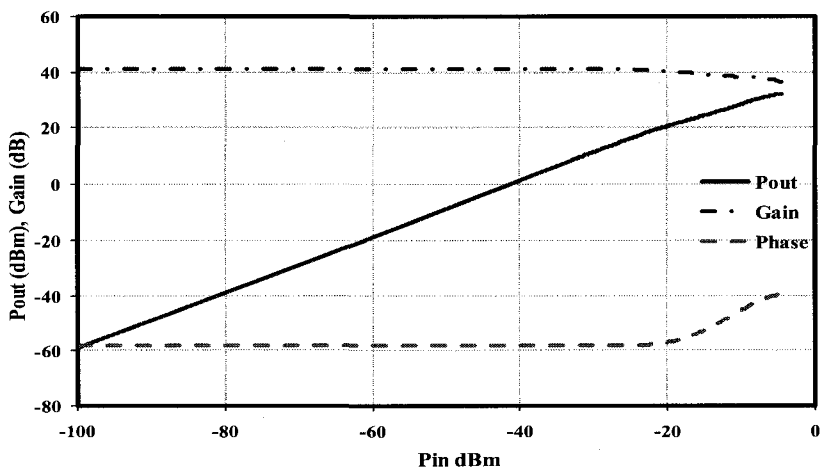


Figure 5-3: The AM-AM, AM-PM characteristics of the used amplifiers.

This architecture has the advantage of keeping the conventional receiver architecture. The receiver has a regular WLAN architecture which contains an RF front end, RF/IF conversion stage, A/D converter and a digital DSP block. In this way, the power efficiency is improved as the combiner is eliminated from this design. In the same time, the LINC branch imbalance effects can be tolerated up to a certain extent [25]. The values of the EVM, PAPR for this 2X1 architecture, assuming an ideal channel, are 0.39% and 3.66 dB respectively. These results show superior performance when compared to the LINC and single branch amplifier. In this configuration, the signals are summed at the receiver side. The system design can benefit from the fact that the two transmitted signals are amplified. This means high power transmitted signal which increases the coverage area of the system.

For comparison purpose, different simulation rounds were carried out for the three architectures: (1) single branch amplifier (Reg. Amp.), (2) LINC (Reg. LINC) and (3) the 2X1 LINC architecture. When applying the filtering action in the 2X1 LINC system and transmitting the branch signals, it is found that the new system efficiency is enhanced by about 3.4 times (from 4.72% to 16.17%).

As depicted in Figure 5-4, one can recognize that the branch signal of the 2X1 LINC complies with the standard transmission mask. The ACPR improved significantly, especially when the least square filter was used. The use of the least square filter gave a sharp stable spectrum; and the ACPR was improved by 36.9 dB when compared to the regular LINC amplifier. In addition, the EVM was almost unaffected as the simulated values are so close. On the other hand, the efficiency was improved greatly due to the elimination of the combiner in the new modified 2X1 LINC. These results imply that the system can tolerate higher channel interference levels and can also self-compensate for LINC imbalances as can be inferred from Table 5-1.

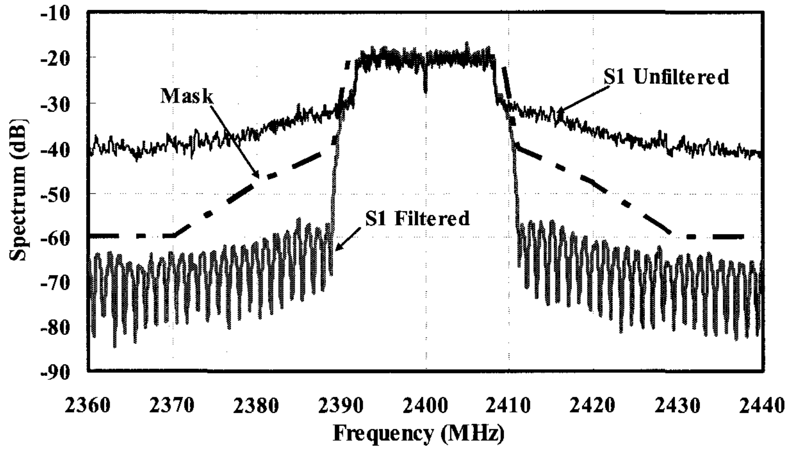


Figure 5-4: Branch signal spectrum before and after filtering for one receiver antenna.

Table 5-1: ACPR, Efficiency, EVM value for the 2X1 system using different filter types, assuming fading channel and added white noise.

Filter Type	*11M Hz*	*20 MHz*	*28 MHz*	*Efficiency.*	*EVM*
Specs	*-20 dBc*	*-28 dBc*	*-40 dBc*		*5.62%*
No Filter	*-10.5dBc*	*-14.7 dBc*	*-16.0 dBc*		*1.50%*
Reg. LINC	*-26.1 dBc*	*-51.1 dBc*	*-56.9 dBc*	*4.72%*	*1.40%*
Least Sq	*-63.1 dBc*	*-70.2 dBc*	*-70.2 dBc*	*16.17%*	*1.53%*
Eq. Ripple	*-42.8 dBc*	*-42.2 dBc*	*-44.5 dBc*	*16.17%*	*1.84%*
Raise Cos	*-40.4 dBc*	*-58.1 dBc*	*-62.0 dBc*	*16.27%*	*1.97%*
Win-Kaiser	*-36.0 dBc*	*-52.5 dBc*	*-58.7 dBc*	*16.30%*	*1.78%*

Meanwhile, the ACPR performance of the system is improved. In fact, it is -26.1 dBc in the case of a regular LINC and -63.1 dBc for the 2X1 LINC at 11MHz frequency offset. A comparison between the 2X1 LINC transmitted signal spectrum and that of the regular LINC is shown in Figure 5-5 . It can be noted from the figure, that the ACPR is improved significantly, especially when the least square filter is used. The use of the least square filter results in a sharp stable spectrum and the ACPR was improved by 43 dB and by 37 dB when compared to the regular amplifier specification and the LINC amplifier, respectively.

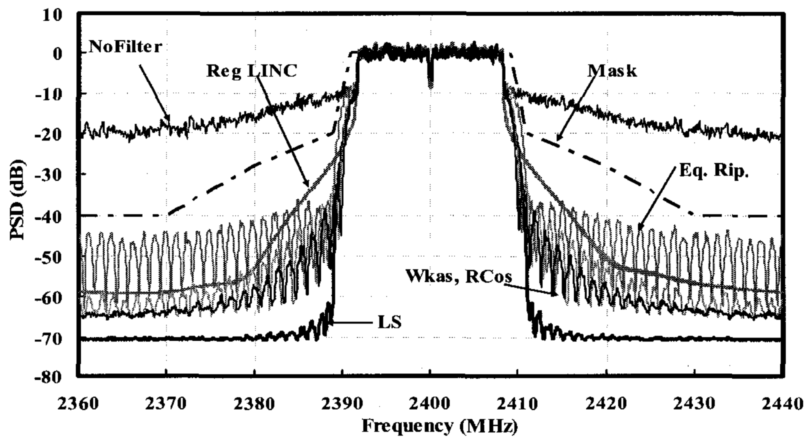


Figure 5-5: Transmitted signal spectrum with respect to the mask for modified 2X1 LINC (using different filters).

In addition, the system efficiency is enhanced due to the removal of the combiner. These results imply that the system can tolerate higher channel interference levels and also can be more robust for impairments due to LINC imbalances. The ACPR improvement for this new transmitter is also illustrated in Figure 5-6 for different input power levels compared to those of the LINC and single branch amplifier. Also the input and output signal spectrums are shown in Figure 5-7.

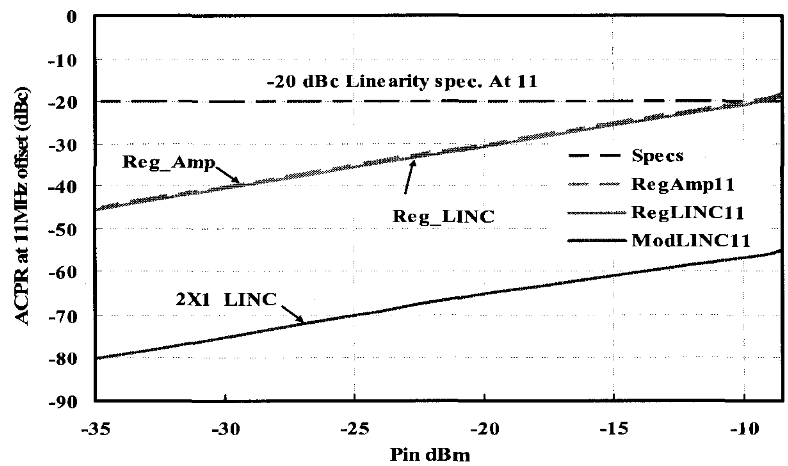


Figure 5-6: ACPR at 11MHz offset for the 2x1 LINC, Regular LINC and regular amplifier for different input power levels.

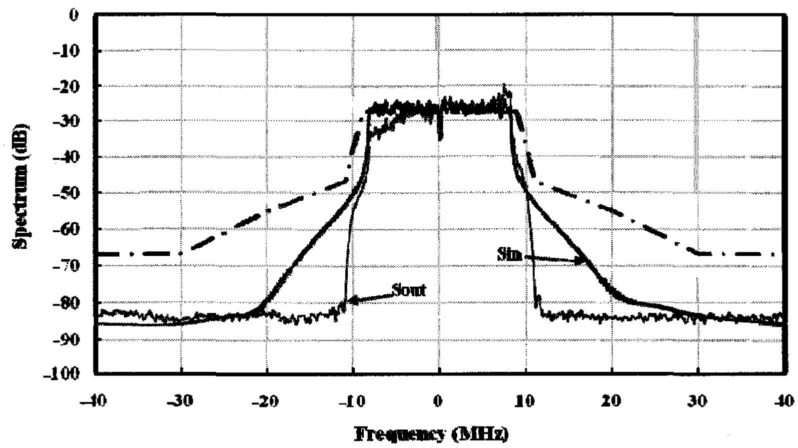


Figure 5-7: Input and output signal spectrum when using one receiver antenna.

5.3 The 2X2 LINC transmitter system

In this proposed modified 2X2 LINC architecture, also the branch signals are filtered to fit the IEEE standard mask, amplified then transmitted. The receiver has two antennas that perform the signal receiving as shown in Figure 5-8. The proposed modified 2X2 LINC architecture transmitter contains a digital signal processing (DSP) and RF front end blocks. The DSP block consists of the SCS that decomposes the baseband input signal S_{in}(t) into the two constant amplitude signals S_1(t) and S_2(t) and then calculates their rectangular representation (I_1,Q_1) and (I_2,Q_2), respectively. As presented in the 2X1 LINC, digital filters are used to shape these signals. The digital shaping low pass filters are used to fit the signal in each branch within the standard transmission mask, thus lowering the out-of-band emissions and improving the ACPR of the resulting system.

The resulting digital IF signals are then converted to analog IF using digital to analog converters (DACs). In the RF front end, the analog IF signals are up-converted to RF and then amplified. Finally, the amplified RF signals are fed to the input port of the transmitter antennas. The receiver contains an RF front end consisting of two branches composed of a low noise amplifier (LNA), a down-converter, an analog to digital converter (ADC) and a digital DSP block. The received RF signals, $S_1^R(t)$ and $S_2^R(t)$ are down-converted to IF, then converted to digital using the ADC. In the DSP block, the equalizer processes of the two signals to cancel the transmitting channel and components imbalance effects.

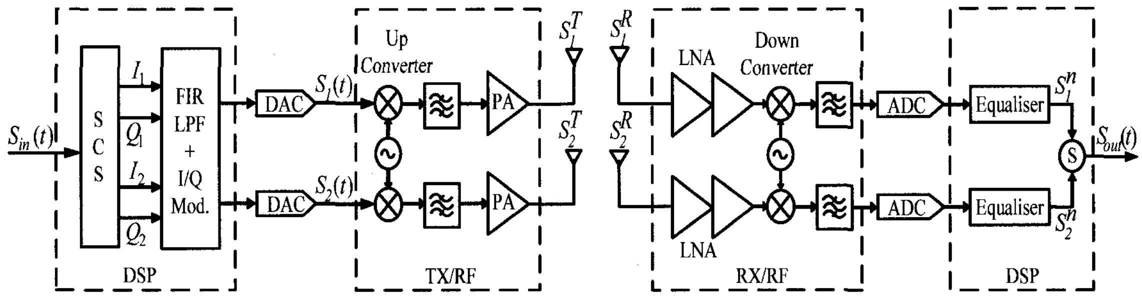


Figure 5-8: Modified 2X2 LINC transceiver architecture.

The signals $S_1^N(t)$ and $S_2^N(t)$ are then recombined to generate $S_{out}(t)$, which should be a replica of the original signal at the transmitter input $S_{in}(t)$. Therefore, the LINC combiner problems are resolved since the two signals are combined at the receiver side and the amplifiers are able to operate at their saturation region i.e. near their peak efficiency. It can be deduced that the LINC imbalance effects will be reduced and can be corrected at the receiver side. The proposed RF front end performance is evaluated using the simulator software ADS. Like the case of the 2X1 LINC, an IEEE 802.11g signal, with a PAPR of about 10 dB, a data rate of 54 Mbps, a 64-QAM modulation and a -10.0 dBm input drive level, was also used in the evaluation.

The LINC was constructed using the two class-AB amplifiers (HMC 408 from Hittite Inc.) used in the 2X1 simulations. In this case, a low-pass equiripple (EQRIP) digital filter with 61 taps was applied on the branch signals (for the in-phase and quadratic components, I and Q). To ensure that the two signals paths are de-correlated two antennas with orthogonal polarization were used. It was also assumed that the wireless radio channels were multi-path Rayleigh fading ones. To evaluate the signal compatibility and study system performance without the channel effect, it was assumed that the channel is ideal with unitary response over the whole frequency range.

Figure 5-9 illustrates simulations results for a regular LINC amplifier and a modified LINC, where Reg-LINC S1 and Mod-LINC S1 are the amplified branch signals for the regular LINC amplifier and the modified LINC, respectively.

The results show that the LINC is superior to regular amplifier, since the back-off was reduced from 9.40 dB to 3.36 dB for the regular LINC. The power-added efficiency of the amplifier for the different architectures was 1.2% for the regular amplifier, 5% for the regular LINC system and around 16% for the modified LINC system.

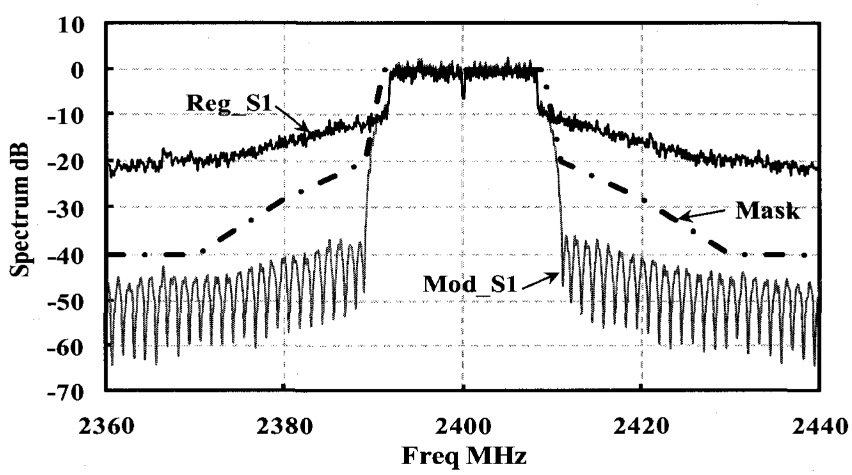


Figure 5-9: Amplifies Branch signals spectrum for regular and modified 2X2 LINC.

It should be mentioned here that due to the combiner removal in the modified LINC, the signal recombining efficiency was raised to 86% compared to 18.7% for regular LINC. This implies a significant improvement in the power efficiency, as it reaches 15.5% for the modified 2X2 LINC amplifier, while it was only 1.2% for a regular amplifier and 3.9% for regular LINC amplifier according to the simulation results and the amplifier's manufacturer data sheet.

The combination of the signals at the receiver remedies the problem of power efficiency of the LINC transmitter. It is important to point out that the combining efficiency is inversely proportional to the PAPR of the input signal. Hence, for a CDMA or OFDM modulated signals, η_b decreasing can seriously affect the overall power-added efficiency of the system.

A realistic channel was then considered, assuming that the two antennas are polarized so that the two channel paths are uncorrelated. The channel model is a typical office environment channel with NonLine-Of-Sight (NLOS) conditions and 50 ns average delay spread. The EVM values are listed in Table 5-2, it could be observed that it increases due to the channel effect. The use of two transmitting/receiving antennas in the case of the modified layout helps to improve the link efficiency and reduce the probability of error. The input Sin and the output Sout signals for the regular and modified LINC architectures are shown in

Figure 5-10, with respect to a zero reference frequency.

Table 5-2: PAPR for branch filtered, output signals back-off and EVM in RMS for the three amplification systems.

Architecture	*S1*	*Sout*	*Backoff*	*EVM*	η
Reg. Ampl.	-	*9.32 dB*	*9.20 dB*	*2.58%*	*1.19%*
Reg LINC	*0.0 dB*	*9.31 dB*	*3.36 dB*	*2.55%*	*3.94%*
Mod.2X2 LINC	*3.68 dB*	*9.60 dB*	*3.84 dB*	*1.75%*	*15.5%*

5.4 Mismatch effects

The mismatch (imbalance) study was carried out for the 2X1 LINC system. As, the system efficiency is enhanced due to the removal of the combiner, results indicate that the system can tolerate higher channel interference levels and can also self-compensate for LINC imbalances [27]. Also, in the proposed 2X1 LINC due to the use of branch digital filtering, a solution for the imbalance issues without any overhead on the system is achieved. The filters improve the ACPR performance of the system and help it to tolerate the imbalance effect.

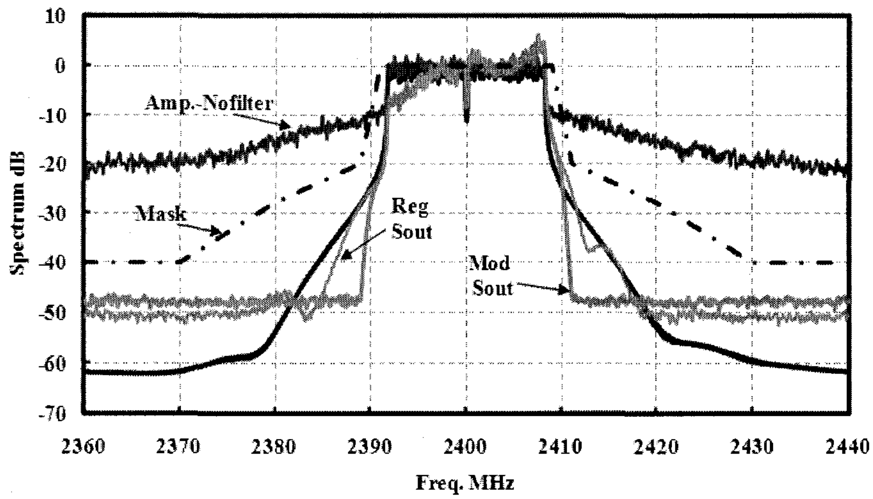


Figure 5-10: Input and output signals spectrum for regular and modified 2X2 LINC.

The imbalance between branch signals magnitudes and phases were studied and demonstrated in Table 5-3. The entries in the table show the EVM values as a metric measuring the system performance when the least square filter was used. Also, it should be mentioned that the ACPR did not change significantly. In this study the ACPR was lowered only by 1.3 dB for the case of 3 degree phase and 0.1 magnitude imbalances were investigated. The efficiency was reduced to 4.22%, due to the degradation in the signal quality. It should be mentioned here that similar results were attained for modified 2X2 LINC amplifier when studied for the same imbalance conditions in magnitude and phase.

Table 5-3: EVM values for different phase and magnitude imbalances for modified 2X1 LINC.

Phase(deg)/Mag.	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*
1	*2.05%*	*2.78%*	*3.48%*	*4.28%*	*5.13%*
2	*3.37%*	*3.88%*	*4.44%*	*5.12%*	*5.88%*
3	*5.04%*	*5.32%*	*5.77%*	*6.34%*	*7.00%*

5.5 Conclusion

In this chapter, a new LINC transceiver architecture suitable for wireless broadband applications using high PAPR signals, such as OFDM and wideband CDMA was proposed. It is based on a modified LINC amplifier in which the signal in the two LINC branches is recombined at the receiver to overcome the problems associated with the combiner losses. Therefore, the overall system efficiency was improved. The new proposed RF front end power amplifier architecture was simulated and results revealed an overall power efficiency improvement.

First a 2X1 LINC layout was proposed, in which two transmitting antennas and one receiving antenna, were employed. It should be mentioned that this new architecture has self adaptation for the imbalance effects between the two LINC paths. Besides, the new proposed architecture was based on DSP implementation where the input signal separation and branch signal filtering are carried out. Signal combining is carried out at the antenna of the receiver side. This new layout is designed to overcome the problems associated with the transmitter combiner losses.

The results show improved back-off operation for the branch amplifier from 9.4 dB for single branch amplifier to 3.66 dB. It is close to that of regular LINC which implies an overall power efficiency improvement from 1.43% for single branch amplifier and 4.72% for LINC, to 16.17% for the proposed 2X1 LINC. The EVM is 1.53% which largely respects the standard specifications (5.6%). In this system, the signals in the two LINC branches are filtered to fit the transmission mask and lower their ACPR. The ACPR performance is greatly improved, which allows some margin in channel interference levels and LINC branch imbalances. Furthermore, the system's overall efficiency is improved as the combiner in the transmitter is removed.

Results have shown that the ACPR was improved by 43 dB when using the least square filter. In addition, the system efficiency was enhanced by 3.4 times when compared to that of a LINC amplifier. The filter action does not affect the system performance in regard to the EVM. This new 2X1 system has the advantage of having standard receiver architecture while delivering an improved system performance regarding efficiency, ACPR and EVM. This results in reducing the system design overhead.

In addition, a 2X2 LINC architecture was introduced and was tested under different channel effects. Simulations were carried out assuming an ideal channel, and amplifier linearization. Results show that, for the proposed architecture, linearization is required to improve the system efficiency and to reduce the EVM. It was found that the digital waveform shaping filter at the transmitter for the 2X2 LINC system is effective in reducing the ACPR. Also, the back-off operation point of the amplifier is improved by 5.6 dB in comparison with regular LINC amplifier. Moreover, the 2X2 LINC EVM is 0.542% which is very low compared to the maximum allowable EVM value of 5.6% in the IEEE standard at 54 Mbps data rate.

Furthermore, the system performance was studied assuming that the channel is a multipath fading channel and has two uncorrelated paths, and different polarizations for the transmitting antennas were used. Results show that the proposed architecture was superior to that of the regular amplifier line up and regular LINC when the same channel layout was used. An EVM value of 1.76% is obtained for the 2X2 LINC architecture. Also the back-off was improved for the modified and regular LINC when compared to that of the regular amplifier. Results show that the back-off operation point of the amplifiers changed from 9.4 dB to 3.8 dB when using the proposed 2X2 LINC architecture, which implies an estimated significant gain in the efficiency when the transmitter is driven by an 802.11g signal. The combiner loss is removed and thereby raising the overall average efficiency of the transmitter from 3.9% for regular LINC to

15.5% for the modified LINC. The calculated EVM level at the transmitter's output is 1.75%, which is low compared to the standard allowed value of 5.6% at the specified transmission rate.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusion

In this dissertation a study of the existing power amplification techniques for wireless amplification is carried out. A comparative study for their performance improvements and tradeoffs was introduced. From that comparison it was concluded that as many techniques had been introduced to improve efficiency, these techniques can be divided into two main categories. The first category is to use Linearizers, like the Digital PreDistortion DPD, which are suitable for high power amplifiers. The second category of power efficiency improvement techniques uses advanced amplification architectures like Doherty, switching amplifiers, Kahn, and LINC. All the proposed techniques are having issues with the linearity especially for broad band multicarrier signals. Except for the LINC that will offer, in principles, an improved efficiency while maintain the signal Linearity.

Therefore the LINC system was chosen as the topic to carry out in this research work to improve its performance, such as signal separation, imbalance between branches and combiner losses. The study was aiming to modify the LINC amplification system and propose a solution to its efficiency problems resulting from the signal combination at the transmitter. The result of this research study is the proposition for the first time of a new system level modified LINC concept in which the combiners are removed and branch signals are first filtered to shape the spectra of the branch's signals into the standard transmission mask, amplified and then transmitted directly to the receiver where they are to be combined. This modified LINC amplification architecture is intended to be used in wireless communication systems to compensate for the power efficiency degradation in the amplification stage due to the LINC hybrid combiner losses.

This new modified LINC system level design concept is an authentic proposal that was used to introduce two novel LINC amplification architectures where the problem of power amplification for wireless systems was tackled. In the new LINC systems, it was suggested, for the first time, to modify the design of the LINC transceiver RF front end, by removing the combiner and transmitting the branch signals after filtering and amplifying them before transmitting the two signals.

The synthesis of the filters was carried out using the commercial software package MATLAB. The filters designed were first used for a regular LINC branch signals shaping, to show the validity of the concept proposed. The regular LINC system was simulated using Agilent Design Software (ADS).

Simulation results for the new design showed that this new RF front end was an interesting solution for transmitters using WLAN OFDM like based wireless communications signals. Different aspects of the system were studied like linearity and efficiency and the main observed conclusions were:

- The branch signals were filtered to fit in the transmitting IEEE 802.11g mask to be able to transmit them in WLAN applications.

- When different low-pass digital filters were tested, the least square filter demonstrated the best results with respect to ACPR performance.

- Simulation results when considering 2X1 modified LINC and channel is an ideal unitary revealed improved back-off operation point of the amplifier (≈ 3.6 dB for the modified LINC compared to 9.4 dB for regular amplifier). Also, the measured EVM was ≈ 0.542% which was very low compared with the standard allowed value of ≈5.6%.

- When considering a multipath fading channel with an added white noise, the response of the modified LINC architectures was satisfactory. The EVM was ≈ 1.6% and the power back off was ≈ 3.69 dB.

- The efficiency of the overall proposed modified LINC system was improved by about eleven times when compared with the efficiency of the regular amplifier and was improved by about four times when compared to the efficiency of the regular LINC.

6.2 Contributions:

The main contributions of this dissertation can be summarized as follows:

- A modification in the DSP implementation of the signal separation unit of the LINC amplifier is proposed, to include a filtering operation of the two branch signals. This results in an improved LINC amplifier system performance in terms of the ACPR and the LINC mismatch [25].

- A novel system level 2X1 LINC amplification solution for the wireless communication systems is introduced. The 2X1 LINC is intended to replace the LINC amplifier in order to avoid the LINC combiner efficiency degradation before transmitting the branch signals [27]. This is a new design concept for the LINC which is proposed for the first time.

- A new 2X2 LINC amplification system level solution for the wireless communication systems is also proposed [26].

- The ACPR performance of the new proposed architectures is improved. In addition, their mismatch immunity is superior to that of the regular LINC system. The main advantage would be the great improvement of the power efficiency of the new systems [25] and [28].

6.3 Future work

A potential avenue to push further this work is to validate the new proposed architectures experimentally by designing, building and testing prototypes for both 2x1 and 2x2 LINC transmitters

The first stage will be to:

First, develop and implement the DSP block that can perform the signal separation process, in addition it should generate the two In phase and Quadrature (*I, Q*) signals components and carry out the filtering process on these components. Second, is to test the performance of the DSP block and use it with different modulated signals, like OFDM, WCDMA, etc. In this stage a great care should be given to the time delay between the two paths and the synchronization.

The second stage will be to construct the RF front end. This will include the two branches with the amplifiers, and incorporate the two transmitting antennas. In this case the two RF branches should be tested for compatibility to make sure that the two branches are matched.

The last stage is to construct the whole transceiver system, test it, and to measure the different performance parameters like BER and EVM, in addition estimate the different stages power efficiency, and compute the overall system efficiency behavior.

Furthermore, for the 2X2 LINC system, the equalization processes of the two received signals to cancel the transmitting channel and components imbalance effects should be tackled more in depth and should be the scope of further investigations.

Of course the evaluation of the proposed schemes with different modulated signals across different platforms is to be assessed. Indeed, the adoption of these new power amplification systems for different wireless communication systems should be considered for future work. In this study the new systems were tested for WLAN applications, the use of these systems for other wireless system applications like base stations and user mobile devices should be the focus of a future work.

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Appendix A: Digital Filtering

Introduction:

A brief introduction to the digital filtering issue is presented in the following section. There are two types of filters which are commonly used for the digital filtering:

1) FIR (Finite Impulse Response).
2) IIR (Infinite Impulse Response).

FIR filters are implemented using a finite number *n* of delay taps on a delay line and *n* computation coefficients to compute the algorithm function. The above structure is non-recursive, a repetitive delay-and-add format and is most often used to produce FIR filters. This structure depends on each new sample and current data value. FIR filters can create transfer functions that have no equivalent in linear circuit technology. They can offer shape factor accuracy and stability equivalent to very high-order linear active filters that cannot be achieved in the analog domain. Unlike IIR filters, FIR filters are formed with only the equivalent of zeros in the linear domain. This means that the taps depress or push down the amplitude of the transfer function. The amount of depression for each tap depends on the value of the multiplier coefficient. Hence, the total number of taps determines the "steepness" of the slope. This can be inferred from the structure. FIR filters offer linear phase (frequency) response in the pass-band [5]. A low pass FIR filter template is shown in Figure A.

Different design techniques are commonly used to develop digital FIR filters: the Window technique, the Equiripple technique and least square technique.

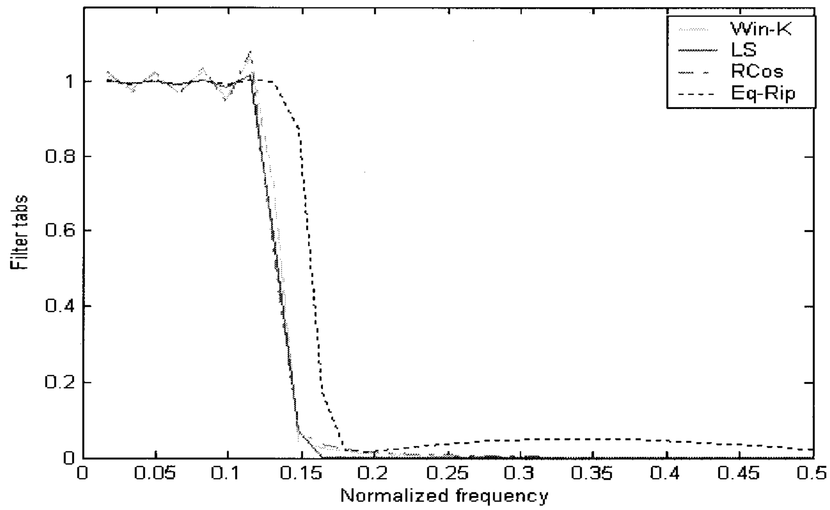

Figure A 1: Tabs of the Low-Pass filter generated in Matlab.

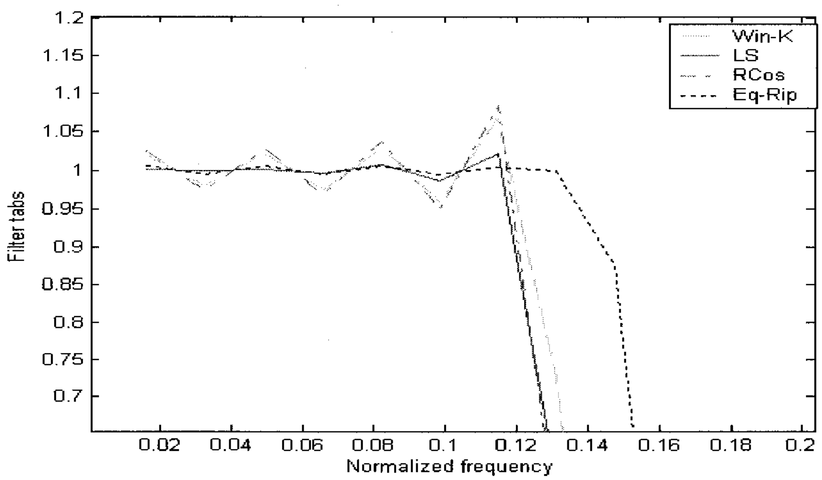

Figure A 2: Zoom on the filter tabs showing the passband.

A. *Window technique*: This simple technique is based on designing a filter using well-known frequency domain transition functions called "windows". The use of windows often involves a choice of the lesser of two evils. Some windows, such as the Rectangular, yield fast roll-off in the frequency domain, but have limited attenuation in the stop-band along with poor group delay characteristics. Other windows like the Blackman, have better stop-band attenuation and group delay, but have a wide transition-band (the bandwidth between the corner frequency and the frequency attenuation floor). Windowed filters are easy to use, are scalable (give the same results no matter what the corner frequency is) and can be computed on-the-fly by the DSP. The latter point means that a tunable filter can be designed with a unique limitation on corner frequency resolution being the number of bits in the tuning word.

B. *Equiripple technique*: An Equiripple design technique provides an alternative to windowing by allowing the designer to achieve the desired frequency response with the fewest number of coefficients. This is achieved by an iterative process of comparing a selected coefficient set to the actual specified frequency response until the solution requiring the fewest number of coefficients is obtained. Though the efficiency of this technique is obviously very desirable, there are some concerns. For Equiripple algorithms, some values may converge to a false result or not converge at all. Therefore, all coefficient sets must be pre-tested off-line for every corner frequency value.

The IIR filter on the other hand is done by the implementation of infinite recursive series. These functions use previously calculated values in future calculations utilizing feedback in hardware systems. Butterworth, Chebycheff and elliptic are examples of such filter. They use essentially the same mathematical structures as their analog counterparts. Due to this, the digital IIR filters exhibit the same or worse non-linear phase characteristics; they suffer from a nonlinear frequency response in the passband.

Appendix B: Published Papers:

Paper 1: A New LINC Transceiver's Architecture for Wireless Radio Systems

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A New LINC Transceiver's Architecture for Wireless Radio Systems

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Abstract-**This paper proposes a new LInear amplification system using Nonlinear Components (LINC) transceiver that utilizes a modified LINC architecture. The drawbacks of the conventional LINC transmitter, which are related to the power efficiency loss due to the analog radio frequency (RF) signal recombination at the LINC output stage, are avoided by combining the decomposed LINC signals digitally at the receiver. Simulation results using a commercial amplifier with a Raleigh fading channel and 802.11a signal demonstrated an obvious improvement of the power efficiency. It increased from 3.9% for regular LINC to 15.5% for the modified LINC system. The quality of the signal was not degraded, as the error vector magnitude metric was kept below 2% at the receiver, which is much lower than the standard requirements.**

Index Terms- **LINC, power amplifiers, wireless radio.**

I. INTRODUCTION

Wireless broadband communication systems require high performance and data capacity, which can be achieved by using more efficient modulation techniques like orthogonal frequency-division multiplexing (OFDM). However, the resulting complex signals have very high peak-to-average power ratio (PAPR) and suffer from wide dynamic range. Highly linear amplifier characteristics are, therefore, required to reduce out-of-band radiation levels, which impose more challenges on the design of RF (radio frequency) front end [1]. LINC (LInear amplification system using Nonlinear Components) amplifiers are intended for applications in which the transmitters should have high accuracy, high output power and high efficiency, while maintaining the linearity of the signal; therefore, LINC architecture may be utilized in systems employing the above-mentioned modulation schemes [2]. However, the LINC technology faces some problems in circuitry such as component mismatch between the two branches, which causes final signal degradation. It also suffers from power efficiency degradation due to the signal recombination. The average efficiency of LINC amplifier depends on the signal dynamics and the combiner's efficiency [3, 4]. The two types of combiners commonly used are the matched power combiner and the Chireix outphasing combiner. The isolated two-way power combiner results in an excellent linearity, but degrades the overall power efficiency of the LINC system [3]. The Chireix outphasing combiner is a lossless combiner that improves the power efficiency, but degrades the linearity of the LINC system.

This paper proposes a new LINC architecture that is intended to overcome the combining problems of the conventional LINC systems by transmitting both branch signals and performing signal combining at the receiver. Compared with the conventional LINC system, the power efficiency of the proposed system is improved, since the combiner element is eliminated from this architecture. The back-off operation point, average transmitter efficiency, error vector magnitude (EVM) and PAPR are computed to evaluate the proposed transceiver efficiency in comparison to that of a conventional LINC transceiver.

This article is organized as follows: in Section 2, a general description of the regular LINC principle is introduced, and a description of the proposed LINC architecture is presented and discussed. Section 3 presents simulation results and performance evaluation; finally, conclusions are presented in Section 4.

II. LINC TRANCIEVER ARCHITECTURES

A. Regular LINC Architecture

The LINC amplifier consists of a signal component separation block (SCS) that divides the baseband signal into two constant amplitude and phase-modulated signals. The two signals are up-converted to the RF signal around the carrier frequency and amplified afterwards. They are summed by a power combiner to reconstruct an amplified, undistorted and modulated RF signal, as shown in Fig. 1. Branch signals generation involves generating two signals: one is a narrow band source signal; the other, a wideband signal that extends into adjacent channels [7]. When the two signal components are recombined, the two source signals are added in-phase, while the wideband signals cancel each other, assuming that there is no phase or gain imbalance in the two branches. If there is imbalance, the cancellation will not be complete and the adjacent channels will be affected. Therefore, the combination process requires more attention. Since the envelope of both branch signals is constant in magnitude, LINC permits the RF power amplifiers to operate near saturation, yielding maximum power efficiency [3]. To apply the two-branch amplification (LINC technique) on a baseband modulated signal having a complex envelope, the input signal $s_{in}(t)$ is decomposed into two constant envelope outphased modulated signals $s_1(t)$ and $s_2(t)$, as shown in Fig. 2. The relations between the signals are given as follows:

$$s_{in}(t) = r(t).e^{j\phi(t)} = s_1(t) + s_2(t) \quad (1)$$

$$r(t) = r_{max}.\cos(\theta(t)) \quad (2)$$

$$s_1(t) = \frac{r_{max}}{2}.e^{j(\phi(t)+\theta(t))} \quad (3)$$

$$s_2(t) = \frac{r_{max}}{2}.e^{j(\phi(t)-\theta(t))} \quad (4)$$

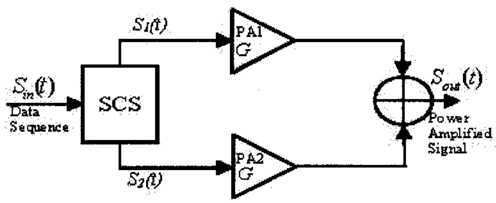

Fig.1. Regular LINC amplifier architecture

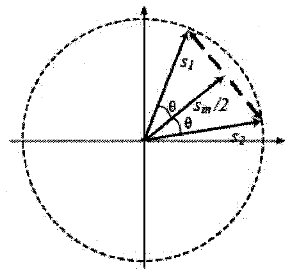

Fig.2. LINC amplifier signals

where r_{max} is the input signal envelope at saturation level. The output signal is assumed to be a replica of the input signal:

$$S_{out}(t) = G(S(t)) = G(S_1(t) + S_2(t)) \quad (5)$$

where G is a complex gain of the amplification stage.

This gain can be different for the two-branch amplifiers due to the possible phase and gain imbalances between the two amplifiers. The power efficiency of the LINC transmitter can be computed using the following formula:

$$\eta = \eta_a \eta_b \eta_c \quad (6)$$

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where η_a is the amplifier's efficiency; η_b is the ratio between the average transmitted power and the intended peak power at the transmitter output, which corresponds to the efficiency of the signal recombining process; and, η_c represents the loss in the combiner itself [8].

The instantaneous combiner efficiency for the matched, isolated combiner can be computed analytically as cos2(θ) [3], which is a function of the decomposition angle θ. This value decreases as θ increases, which corresponds to low signal conditions: this is the most probable case for the signals used in 3G and 4G communication systems. The efficiency increases as θ decreases, which corresponds to signal peaks, as illustrated in Fig. 2.

B. Modified LINC Architecture

The proposed architecture is a modified LINC architecture, which transmits amplified branch signals, and has signal combination occurring at the receiver, as shown in Fig. 3. The transmitter contains a digital signal processing (DSP) and RF front end blocks. The DSP block consists of the SCS that decomposes the baseband input signal Sin(t) into the two constant amplitude signals S1(t) and S2(t), and then calculates their rectangular representation (I1,Q1) and (I2,Q2), respectively. Digital filters are used to shape these signals. The resulting digital intermediate frequency (IF) signals are then converted to analog IF using digital to analog converters (DACs). In the RF front end, the analog IF signals are up-converted to RF and then amplified. Finally, the amplified RF signals are fed to the input port of the transmitter antennas. Indeed, the LINC decomposition generates two constant envelope phase-modulated signals. These signals extend into adjacent channels, resulting in an out-of-mask signal violation. Consequently, these signals are not compliant with standards and cannot be broadcasted to air. Shaping filters after the LINC decomposition process are, therefore, required for the proposed architecture to suppress this spectrum regrowth of the decomposed signals. However, these filters will introduce amplitude modulation (AM) effects in the decomposed signals, which necessitate linearizing the amplifiers. The digital predistortion (DPD) technique is utilized [5].

The receiver contains an RF front end consisting of two branches, each of which is composed of a low noise amplifier (LNA), a down-converter, an analog to digital converter (ADC) and a digital DSP block. The received RF signals $S_1^R(t)$ and $S_2^R(t)$ are down-converted to IF; then converted to digital using the ADC. In the DSP block, the equalizer processes the two signals to overcome the transmitter masking, and channel and components imbalance effects using the technique described in [6]. The signals $S_1^{"}(t)$ and $S_2^{"}(t)$ are then recombined in the digital domain to generate S_{out}t(t), which is a replica of the original signal at the transmitter input Sin(t). In this way, the problem of the LINC combiner can be resolved, since the two signals are combined at the receiver side in digital domain and are able to operate the amplifiers at or near their peak efficiency. The branch imbalance error will be limited and can be corrected at the receiver side.

III. PERFORMANCE EVALUATION

The performance of the proposed RF front end is evaluated using the commercial circuit simulator software Advanced Design System, from Agilent technologies. An IEEE 802.11g signal, with a PAPR of about 10 dB, a data rate of 54 Mbps, a 64-QAM modulation and a -10.0-dBm input drive level, was also used in the evaluation. The LINC was constructed using two class-AB amplifiers (HMC 408 from Hittite Inc [9]). The small signal gain and the saturated output power of the amplifiers were 20 dB and 32.5 dBm, respectively. The different system components like the combiner were assumed to be ideal. A low-pass equiripple (EQRIP) digital filter with 61 taps was applied to the branch signals (in-phase, I, and quadratic, Q, components). To de-correlate the signal paths, two antennas with orthogonal polarization were used. It was also assumed that

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the wireless radio channels were multi-path Raleigh fading ones.

The channel was first assumed to be ideal with unitary response over the whole frequency range. This assumption was made to evaluate the signal compatibility and study system performance without the channel effect. Results for a regular LINC amplifier and a modified LINC are illustrated in Fig. 4, where Reg-LINC S1 and Mod-LINC S1 ($S_1^r(t)$) are the amplified branch signals for the regular LINC amplifier, and modified LINC, respectively. It can be seen from Fig. 4 that the modified LINC branch amplified signal $S_1^r(t)$ that would be transmitted is complying with the mask.

The PAPR of the input and output signals, the value of EVM and the back-off values for the regular amplifier, regular and modified LINC are listed in Table I. It is clear that the LINC was superior to regular amplifier, since the back-off was reduced from 9.40 dB to 3.36 dB for the regular LINC and 3.8 dB for the modified LINC system. The power-added efficiency of the amplifier for the different architectures was 5% for the regular amplifier, 21% for the regular LINC system, and finally 18% for the modified LINC system. The signal recombining efficiency for regular LINC was 18.7%, while the output back-off efficiency for the regular amplifier was 23.8%, and 86% for modified LINC transmitter. This implies a significant improvement in the power efficiency, from 1.2% for a regular amplifier to 3.9% for regular LINC system to 15.5% in the case of the modified LINC amplifier, according to the simulation results and the amplifier's manufacturer data sheet [9].

The efficiency of the new architecture was raised, as any power efficiency loss due to the signal combining structure was avoided. Thus, the overall power efficiency of the proposed system is improved, since the LINC combiner problem is eliminated by combining the signal at the receiver, and the amplifiers working near saturation. This combination of the signal digitally at the receiver totally remedies the problem of power efficiency of the LINC transmitter. It is important to point out that the combining efficiency is inversely proportional to the PAPR of the input signal; hence, for a code division multiple access (CDMA) or OFDM modulated signal, η_b decrease can seriously affect the overall power-added efficiency of the system.

A realistic channel was then considered, assuming that the two antennas are polarized so that the two channel paths are uncorrelated. The channel model is a typical office environment channel with nonline of sight (NLOS) conditions and 50ns average delay spread. The values of EVM are listed in Table II. One can observe that it increases due to the channel effect. The use of two transmitting/receiving antennas in the case of the modified layout helps to improve the link efficiency and reduce the probability of error. The input S_{in} and the output S_{out} signals for the regular and modified LINC architecture are shown in Fig. 5, with respect to a zero reference frequency. The efficiency figures are the same in this case, as in Table I.

VI. CONCLUSION

This work proposes a new LINC transceiver architecture suitable for wireless broadband applications using high PAPR signals such as OFDM and wideband CDMA (WCDMA). It is based on a modified LINC amplifier, in which the signal in the two LINC branches is recombined at the receiver to overcome the problems associated with the combiner losses; thus, the overall system efficiency is improved. Results show that the back-off operation point of the amplifiers changed from 9.4 dB to 3.8 dB when using the new proposed LINC architecture, which implies an estimated significant gain in the power-added efficiency from about 5% to 18% for transmitters driven by an 802.11g signal. Also, the combiner loss is removed, thereby raising the overall average efficiency of the transmitter from 3.9% for regular LINC to 15.5% for the modified LINC. The calculated EVM level at the output of transmitter is 1.75%, which is low compared to the standard allowed value of 5.6% at the specified transmission rate.

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Table I. PAPR in dB for branch filtered signals S_1, output S_{out}, backoff, EVM in RMS and average efficiency for the system assuming an ideal channel.

Architecture	S_1	S_{out}	Backoff	EVM	η
Reg. Ampl.	---	9.25 dB	9.40 dB	0.47%	1.19%
Reg LINC	0.00 dB	10.28 dB	3.36dB	0.39%	3.94%
Mod. LINC	3.66 dB	10.29 dB	3.80 dB	0.54%	15.5%

Table II. PAPR for branch filtered, output signals back-off, and EVM in RMS for the three amplification systems assuming fading channel, and AWGN.

Architecture	S_1	S_{out}	Backoff	EVM
Reg. Ampl.	-	9.32 dB	9.20 dB	2.58%
Reg LINC	0.0 dB	9.31 dB	3.36 dB	2.55%
Mod. LINC	3.68 dB	9.60 dB	3.84 dB	1.75%

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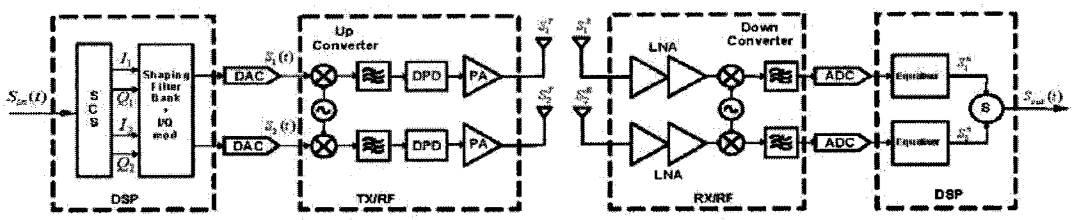

Fig.3. Modified LINC transceiver architecture

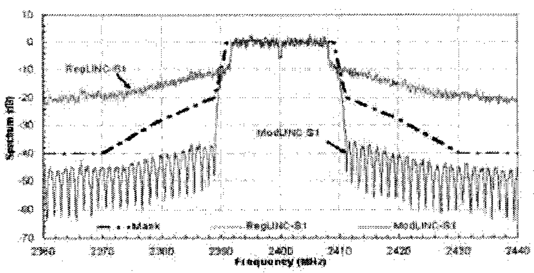

Fig.4. Amplifies Branch signals spectrum for regular and modified LINC

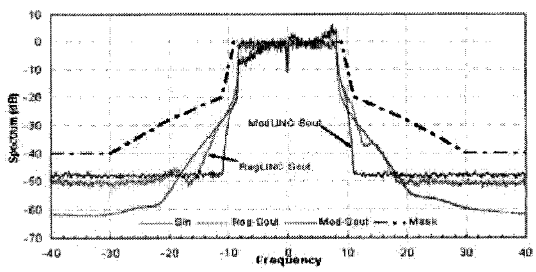

Fig.5. Input and output signals spectrum for regular and modified LINC, under real channel condition

Paper 2: A Modified LINC Amplification System for Wireless Transceivers

A Modified LINC Amplification System for Wireless Transceivers

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***Abstract*—A new RF modified linear Amplifier using Nonlinear Components (LINC) architecture for wireless communication links is proposed and evaluated in this work. The layout of the new architecture is presented and the simulation results are presented to show the performance under different operation conditions and channel types. Results show that the overall power efficiency of this architecture is improved by more than 400% when compared with that of the regular LINC amplifier architecture.**

Keywords; LINC, Power Amplifiers, Wireless Communication.

I. INTRODUCTION

The recent growth in the wireless communications had made it the most important communications media, at the same time its use is increasing dramatically. This is a result of an increased demand for wireless services providing higher data rates, and more universal interface for a variety of services. The evolution of the WLAN (Wireless Local Area Networks) technologies is forcing to adapt new technologies and standards, such as, OFDM, WCDMA. modulation schemes. The use of OFDM scheme for data modulation in WLAN applications is advantageous over other modulation schemes because of its efficiency in the use of the tight bandwidth and easy solution of symbol interference and fading problem without having to use elaborate equalization techniques. That helps to incorporate high data rates and solves the fading problem in time dispersive channels that is why OFDM is considered the most promising modulation scheme for future applications. However, the resulting OFDM complex signals are containing high dynamics with increased signal PAPR (Peak to Average ratio). So in order to reduce out of band radiation levels, they require highly linear amplifier characteristics, imposing more challenges on the design of the RF front end of the transceiver link. Whilst, LINC amplifier is projected for applications in which high accuracy of the transmitted signals and high output power level should be maintained while preserving the signal linearity. So the use of the LINC amplifier architecture for WLAN systems with OFDM modulation systems is introduced [1]. On the other hand LINC architecture is inherited with its own problems like the problem of power efficiency degradation due to power dissipated in the branch signals combination Process [2]. The average efficiency of LINC depends on signal dynamics and the combiner efficiency [3, 4]. Also circuitry and component mismatch between the two branches cause final signal degradation [5, 6, 7]. The new architecture would have the advantage of using two nonlinear amplifiers working at their high efficiency operation region (near saturation), then transmits the branch signals removing the transmitter combiner efficiency problems and also would add the flexibility of compensating for the signal distortions due to the channel and LINC branches imbalance (in gain and delay), at the receiver in digital baseband equalization process.

This work is proposing a modified LINC architecture for OFDM-based communication transceivers and studying the performance of this system The error vector magnitude (EVM) and peak to average power ratio (PAPR) are computed to evaluate the system performance, also the back off operation point is considered for power added efficiency evaluation. This paper is structured as follows: section II is a description of the regular LINC principle, and the modified LINC architecture, Section III presents results and performance evaluation. While section IV presents conclusions.

II. LINC TRANSCEIVERS

A. Regular LINC scheme

The regular LINC is composed of a signal component separation block (SCS), two identical power amplifiers, and a power combiner. The SCS divides the baseband signal into two constant amplitude, phase modulated signals, the two signals are upconverted to the carrier frequency, amplified, and are then summed by the power combiner, to reconstruct an amplified, undistorted replica of the baseband signal as shown in Fig. 1. By this approach the RF power amplifiers are operated near their saturation, while the two branch signals yielding maximum amplifier efficiency and high linearity as the envelope of both signals is constant in magnitude [2]. In order to apply the two-branch amplification (LINC technique) to a modulated signal $S_{in}(t)$ having complex envelope, then it can be decomposed into two signals $s_1(t)$, $s_2(t)$, as follows:

$$s_{in}(t) = r(t).e^{j\phi(t)} = s_1(t) + s_2(t) \quad (1)$$

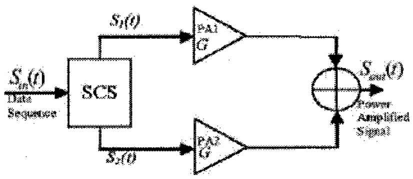

Fig. 1 Regular LINC amplifier architecture

$$r(t) = r_{max}.\cos(\theta(t)) \tag{2}$$

$$s_1(t) = \frac{r_{max}}{2}.e^{j(\phi(t)+\theta(t))} \tag{3}$$

$$s_2(t) = \frac{r_{max}}{2}.e^{j(\phi(t)-\theta(t))} \tag{4}$$

Where r_{max} is the input signal envelope at saturation level. The signal sent is assumed to be a replica of the input signal, $S_{in}(t)$ and $S_{out}(t)$ is given as:

$$s_{out}(t) = G\{s_1(t) + s_2(t)\} \tag{5}$$

where G is the amplifier complex gain.

A. Modified LINC Architecture

In this modified LINC architecture, the amplified branch signals are transmitted directly before being combined. The Signal combination occurs at the receiver by the receiving antenna as depicted in Fig. 2. The transmitter contains a digital DSP block, and RF front end that includes the PA. The digital shaping filters are used to fit the signal in each branch in the standard mask; this would add dynamics to the signal, and increase its PAPR. The receiver contains an RF front end, consisting of a Low noise amplifier, an RF/IF converter, A/D converter and a digital DSP block. The DSP block is used to process the received signal to overcome the transmitter masking effect and channel effects. In this manner the power efficiency is improved. In the same time, the branch imbalance could be treated following the technique introduced in [7]. The values of the EVM, PAPR and back off for the signal to be transmitted for this modified architecture assuming the channel is an ideal channel is 0.39% and 3.66dB, 3.66dB respectively. The Results are showing that this modified architecture is showing superior performance when compared to the regular amplifier based transceiver system.

II. Results Evaluation

To evaluate the performance of the proposed system in a more practical manner, an indoor multipath fading channel was assumed. In addition, the added white noise effects in the simulation are considered. Also, it was assumed that using antenna polarization the two channels are uncorrelated, and that each channel follows a multipath Raleigh fading model. The test signal employed here was an IEEE 802.11g OFDM signal having 2.4 GHz frequency, having 20 MHz bandwidth, 64 QAM modulation, 54 Mbps data rate and signal power of -10.0 dBm. Furthermore, the LINC was constructed using two class AB amplifiers (HMC 408 from Hittite Inc); where their characterizing data (AM-AM, AM-PM, and the digital predistortion (DPD) characteristics) were measured to be used in the simulations [8]. The attenuation in the two LINC paths can be neglected. The amplifiers in the LINC are linearized using the DPD, because filtering the branch signals, shaping them in the standard mask, introduces dynamics in the signal. The time domain representation of the branch signal has constant envelope, while its spectrum ($s_1(t)$ unfiltered) shown in Fig. 3. The filter is used to lower the amplitudes of the frequency components out of the mask that results in a signal with a variable envelope in time domain. The PAPR increases from 0.0dB to 3.66dB, forcing the use of linearization for the amplifiers.

In this study, simulations were carried out for all the three transmitter architectures regular single branch amplifier (Reg. Amp.), regular LINC (Reg. LINC), and Modified LINC. The equiripple filter is applied to the branch signals in the modified architecture. Results show that the branch signals to be transmitted after filtering follow the transmission mask as shown in Fig. 3. The channel model was taken to be a typical office environment channel with NLOS conditions and 50 ns average delay spread. The results obtained in the case of regular single branch amplifier (Reg. Amp.), and a regular LINC (Reg. LINC), are used as a reference for comparison purposes. The values of PAPR for the output signal are listed in table I, and for the branch signal is 3.66 dB for the modified LINC (due to filtering), and roughly zero for the regular LINC (constant amplitude signal). The value of EVM listed in table I, is 1.86%, which is less than the standard limit of 5.6% at the transmission rate used. Meanwhile the value of EVM for regular amplifier is 2.58%, whilst it is 2.55% in the case of regular LINC. The branch signal is shown in Fig. 4, while the input and output signals are shown in Fig.4 both for the modified architecture.

The LINC amplifier power efficiency is calculated as follows:

$$\eta = \eta_a \eta_b \eta_c \tag{5}$$

where η_a is the amplifier's efficiency; η_b is the ratio between the average transmitted power and the intended peak power at the transmitter output; which corresponds to the efficiency of the signal recombining process; and η_c

represent the efficiency of the combiner itself it is considered here to be 100% efficient [1]. The instantaneous combining efficiency for the matched, isolated combiner can be computed analytically as $cos^2(\theta)$ [3], Which is a function of the decomposition angle θ. The efficiency value would decrease as θ increases, for low signal conditions, which is the probable case for complex signals used in 3G and 4G communication systems. While, the efficiency would increases as θ decreases, corresponding to signal peaks. It is found that the efficiency for the modified LINC is 16.3% which is larger 4 times than that of a regular LINC, as shown in table I

III. Conclusion

A new RF power amplifier architecture suitable for OFDM transceivers is proposed. It is based on a modified LINC amplifier in which the signals in the two LINC branches are filtered, amplified, transmitted and then combined by the receiver antenna, to overcome the problems associated with the transmitter combiner losses. Results show improved back-off operation point of the amplifier to 3.66 dB compared to 9.4 dB for regular amplifier, it is close to that of regular LINC, which implies an overall power efficiency improvement from 1.43% for regular amplifier, and 3.94% for regular LINC, to 16.3% for the proposed modified LINC. The EVM is 1.86% which is low compared with the standard allowed value of 5.6%.

Table I. PAPR (dB) for Branch filtered signals S_1, Output, S_{out}, Backoff, EVM (RMS), Average Efficiency

Architecture	S_1	S_{out}	Backoff	EVM	η
Reg. Ampl.	---	9.25 dB	9.40 dB	2.58%	1.43%
Reg LINC	0.0 dB	9.6 dB	3.36dB	2.55%	3.94%
Mod. LINC	3.66dB	9.61dB	3.66 dB	1.86%	16.3%

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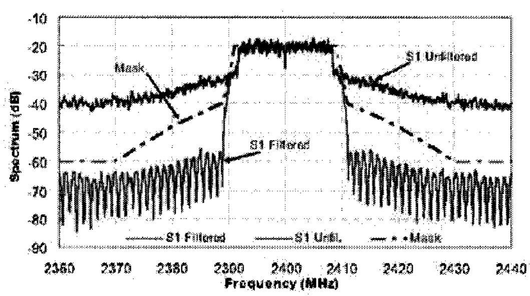

Fig. 3: Branch signal spectrum before and after filtering.

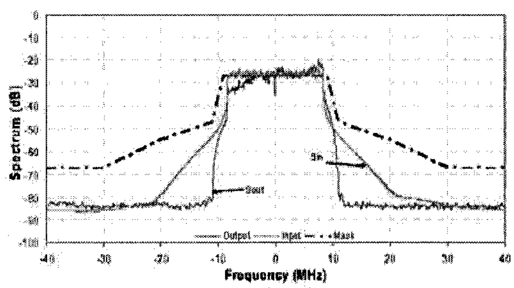

Fig. 4: Input and output signal spectrum for Modified LINC

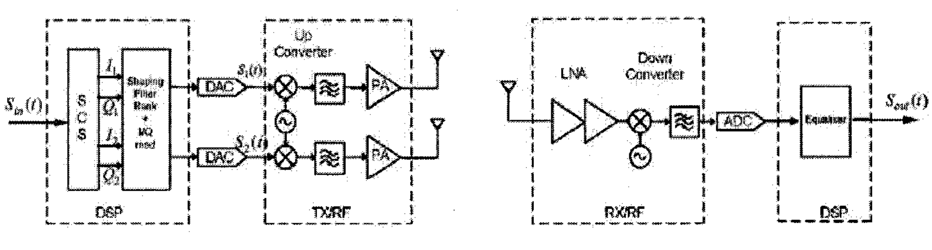

Fig. 2: Detailed layout of the proposed Modified LINC architecture.

Paper 3: A 2x1 LINC Transceiver for Enhanced Power Transmission in Wireless Systems

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Research Letter

A 2×1 LINC Transceiver for Enhanced Power Transmission in Wireless Systems

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Recommended by Peter Jung

A 2×1 LINC transceiver based on linear amplification using nonlinear components (LINC) architecture for wireless systems applications is proposed. The layout of the new architecture is presented and the simulation results show that the overall power efficiency of this architecture is superior by more than 300% when compared with that of a regular LINC amplifier. Also the adjacent channel power ratio (ACPR) is lowered to −64.2 dBc, compared to −26.1 dBc for regular LINC, which improves the system immunity against complex gain imbalances between LINC branches.

1. INTRODUCTION

The trend in the information technology field is pushing towards systems that offer higher transfer rates and free mobility. That implies moving towards wireless communication systems using digital modulation schemes to acquire maximum benefit from the scarce and crowded spectrum. At the same time, these systems should be more efficient concerning power handling. The employment of complex modulation schemes to efficiently use the available tight bandwidth and incorporate higher data rates comes with complex modulated signals containing high dynamics with increased peak-to-average power ratio (PAPR). This necessarily requires linear amplification over a large power range, forcing the use of a low efficiency power amplifier working in a high back off which results in lower efficiency. Meanwhile in the literature, one can find several approaches for improving the power amplifier (PA) efficiency while maintaining an acceptable linearity. One of which is the LINC power amplifier that is intended for use in wireless systems since it offers high efficiency and linearity [1–4]. In the meantime, signal linearity is an important factor in determining how well a wireless system works, be it a cellular network, WLAN network, and so forth. Indeed, power amplifiers are the main source of nonlinearities in these systems. Also emissions in the adjacent channel are of a great concern as they reduce the number of active users who can be operating at the same time. The bit error rate (BER) also increases due to those emissions reducing the system quality of service (QoS). The nonlinear behavior of the system is determined by ACPR, which can be used to accurately show the linearity of a system. Also complex signals like OFDM impose strict requirements on transmitted signal linearity to meet the error vector magnitude (EVM) specification.

In this paper, a 2×1 amplification system is proposed. Simulated results of the power efficiency, EVM and ACPR performance, as well as the assessment of branches imbalance effects on the system performance are presented. In Section 2, a brief description of the LINC concept is presented; Section 3 introduces the 2×1 LINC transceiver; while Section 4 presents the results of efficiency, ACPR, and EVM performances. Section 5 shows the imbalance behavior of the system. Finally, conclusions are presented in Section 6.

2. LINC AMPLIFIER

A regular LINC amplifier consists of a signal component separation block (SCS), two identical power amplifiers, and a combiner. The SCS divides the baseband signal into two constant amplitude, phase-modulated signals. The two signals

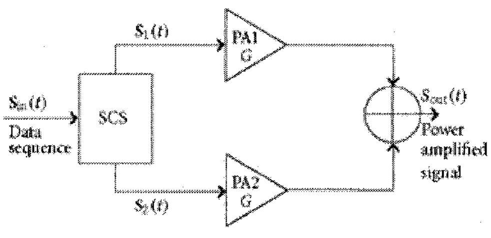

Figure 1: Regular LINC amplifier architecture.

are upconverted to RF, amplified, and summed by the power combiner to reconstruct an amplified replica of the input signal, as shown in Figure 1. In this manner, the RF power amplifiers are operated at saturation, and the two branch signals yield maximum amplifier efficiency and high linearity as the envelope of both signals is constant in magnitude [3–5].

3. THE 2×1 LINC TRANSCEIVER

In the proposed 2×1 LINC architecture, the amplified branch signals are transmitted, after being filtered to fit the standard mask for transmission, and amplified [5]. The receiver antenna performs the signal combination as shown in Figure 2. The transmitter contains a DSP block and a Tx RF front end. The DSP block contains the SCS and shaping filters. The SCS decomposes the baseband signal, $S_{in}(t)$, into two constant amplitude signals, $S_1(t)$ and $S_2(t)$, and calculates their rectangular representations (I_1, Q_1, I_2, Q_2), respectively. The digital shaping filters are used to fit the signal in each branch within the standard mask, and help lower out-of-band emissions, thus improving the ACPR of the resulting system. Filtering the branch signals of the LINC architecture introduces dynamics in the signal (the PAPR increases from 0.0 dB to approximately 3.6 dB), necessitating the use of linearization for the amplifiers, as they are working near saturation. Also the LINC transmitter contains the two antennas which are close enough such that it can be assumed that both transmitted signals will experience the same channel effect. This effect will be corrected for by the equalization algorithm performed at the receiver.

The receiver is of a regular WLAN architecture containing an RF front end, which consists of Rx receiver, RF/IF conversion stage, A/D converter, and a digital DSP block. In this way, the power efficiency is improved as the combiner losses are eliminated. At the same time, the LINC branch imbalance effects can be tolerated up to some extent. The values of the EVM and PAPR for this 2×1 architecture assuming an ideal channel are 0.39% and 3.66 dB, respectively. These results show superior performance when compared to the LINC and single branch amplifier.

4. EVALUATION OF SYSTEM PERFORMANCE

The performance of the proposed 2×1 LINC system is evaluated through simulations; the advanced design system (ADS)

Raleigh multipath fading channel was considered, as well as additive white Gaussian noise (AWGN) effects. An IEEE 802.11g OFDM signal with a 2.4 GHz frequency, 20 MHz bandwidth, 64 QAM modulation, 54 Mbps data rate, and signal power of −10.0 dBm was used. Two class AB amplifiers (HMC 408 from Hittite Inc.) were utilized to construct the LINC. The digital predistortion (DPD) technique was used to linearize the amplifiers to compensate for the PAPR increase due to filter effect. The LINC amplifiers characterizing data, (the AM-AM, AM-PM, and the synthesized AM-AM and AM-PM of the DPD) were measured and used in this study. The attenuation in the two LINC paths was assumed to be negligible. Meanwhile, the MATLAB software was used for filter synthesis. Digital FIR lowpass filters, with an order of 60, were used.

Simulations were carried out for the architectures single branch amplifier (Reg. Amp.), LINC (Reg. LINC), and 2×1 LINC. Results show that the branch signals to be transmitted after filtering fit within the transmission mask. Results also show that the efficiency of a regular LINC amplifier is 4.72%, while the EVM is 1.4% as shown in Table 1. When applying the filtering action in the 2×1 LINC system, and transmitting the branch signals, it is found that the new system efficiency is enhanced by about 3.4 times (from 4.72% to 16.17%), and the EVM remains almost constant. The branch signal of the 2×1 LINC system is complying with the standard mask; meanwhile the ACPR performance of the system is improved. A comparison between the 2×1 LINC transmitted signal spectrum and that of the regular LINC in adjacent channels is shown in Figure 3. It can be noted from the figure that the ACPR had improved significantly, especially when the least square filter was used. The use of the least square filter results in a sharp stable spectrum; and the ACPR was improved by 43 dB and by 37 dB when compared to the standard specification and the LINC amplifier, respectively. In addition, the system efficiency is enhanced due to the removal of the combiner. This result implies that the system can tolerate higher channel interference levels and also can self-compensate for LINC imbalances. The ACPR improvement for this new transmitter is also illustrated in Figure 4 [5] for different input power levels compared to those of an LINC and single branch amplifier.

5. IMBALANCE EFFECTS

The parallel RF branches of the LINC transmitter suffer from unavoidable difference in their magnitudes and phase responses. Imbalance effects between the two LINC branches are studied. This effect was corrected using different techniques that are complex implementations [6]. Meanwhile in the proposed 2×1 LINC, and due to using the branch digital filtering, a solution without any overhead on the system is achieved. The filters improve the ACPR performance of the system and help it to tolerate the imbalance effect.

Table 2 shows the imbalance values between the two branch signals' magnitudes and phases, the entries in the table show the EVM values. The ACPR did not change significantly: it was lowered by only 1.3 dB in the case when a 3-

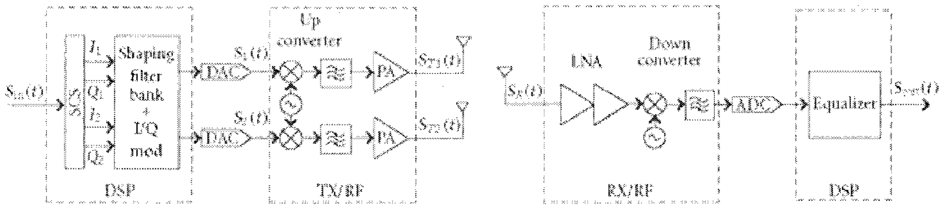

Figure 2: Detailed layout of the proposed 2 × 1 LINC architecture.

Table 1: ACPR, efficiency, and EVM without and with filtering.

Filter type	ACPR@11 MHz	ACPR@20 MHz	ACPR@28 MHz	Efficiency	EVM
Specs	−20 dBc	−28 dBc	−40 dBc	—	5.62%
Reg. LINC	−26.1 dBc	−51.1 dBc	−56.9 dBc	4.72%	1.40%
2 × 1 LINC	−63.1 dBc	−70.2 dBc	−70.2 dBc	16.17%	1.53%

Table 2: EVM values for different phase and magnitude imbalances.

Phase/Mag.	0.1	0.2	0.3	0.4	0.5
1°	2.05%	2.78%	3.48%	4.28%	5.13%
2°	3.37%	3.88%	4.44%	5.12%	5.88%
3°	5.04%	5.32%	5.77%	6.34%	7.00%

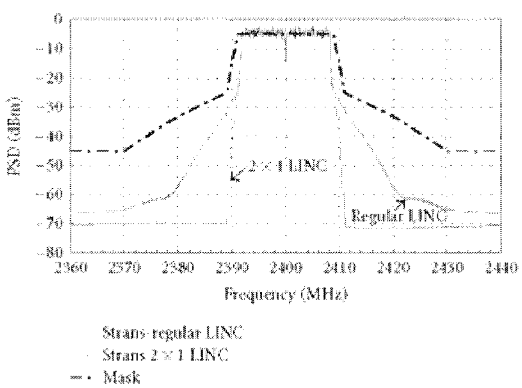

Figure 3: Comparison of the spectrum of transmitted signals of 2×1 LINC system $S_{T2}(t)$ and the regular LINC system $S_{out}(t)$ shown in Figure 1, with respect to the mask of the 802.11g standard.

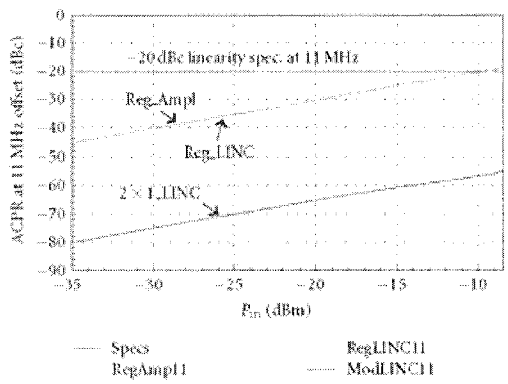

Figure 4: ACPR at 11 MHz offset for the 2 × 1 LINC, regular LINC, and regular amplifier for different input power levels.

In addition, the efficiency was lowered to 4.22%. Of course, cases where the EVM exceeded 5.6% are not accepted as they were over the standard limit.

6. CONCLUSION

A 2 × 1 LINC transceiver architecture suitable for wireless transceivers is proposed. It is based on DSP implementation where the LINC input signal separation and branch signal filtering are carried out. The signal combining is carried out at the antenna of the receiver side. This new layout is designed to overcome the problems associated with the transmitter combiner losses. The results show improved backoff operation for the branch amplifier from 9.4 dB for a single branch amplifier to 3.66 dB. It is close to that of regular LINC, which implies an overall power efficiency improvement from 1.43% for a single branch amplifier, and 4.72% for LINC, to 16.17% for the proposed 2 × 1 LINC. The EVM is 1.53% which is low compared with the standard allowed value of 5.6%. In this system, the signals in the two LINC branches are filtered to fit the transmission mask and lower their ACPR. The ACPR performance is greatly improved, which enables the toleration of higher channel interference levels and LINC branch imbalances; meanwhile the system's overall efficiency is improved as the combiner in the transmitter is removed.

Results show that the ACPR is improved by 43 dB when using the least square filter. In the meantime, the system efficiency is enhanced by 3.4 times when compared to that of an LINC amplifier. The filter action does not affect the system performance in regard to the EVM, as the results show. This new 2×1 system has the advantage of having standard receiver architecture while delivering an improved system performance regarding efficiency, ACPR, and EVM.

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Paper 4: THE DSP Implementation of the LINC Amplifier to Improve ACPR and Imbalance Performance

THE DSP IMPLEMENTATION OF THE LINC AMPLIFIER TO IMPROVE ACPR AND IMBALANCE PERFORMANCE

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Abstract—**This paper is projected towards improving the adjacent channel power ratio (ACPR) for LInear amplification using Nonlinear Component (LINC) power amplifiers in OFDM based wireless systems using digital baseband filtering for branch signals. The IEEE802.11g standard, which operates at 2.4 GHz, is used to show the amount of improvement. Results show that the ACPR is improved using a least square filter, from -26.1dBc to -63.8dBc, without deteriorating the overall system power efficiency.**

I. INTRODUCTION

The ever growing and evolving market of wireless communication systems is advancing towards new systems that are more efficient in using the scarce and crowded spectrum, and also more efficient with respect to power consumption. In order to ensure quality of service, the use of the available spectrum requires taking care of the emissions caused by the transmitted signal in the adjacent channels. The larger the signal in the adjacent channel bandwidths, the greater the distortion becomes in the users' channel bandwidths. For a wireless system, this means a reduced number of users can be operating at one time and also a degradation of the quality in other users' signal bandwidth by causing interference, distortions and increasing the bit-error rate (BER), given the accumulation of noise introduced into other users' channels.

One of the most important specifications in a wireless transmitter is the adjacent channel power ratio (ACPR), which measures the amount of nonlinear distortions caused by the transmitted signal. The ACPR and the modulation scheme determine the maximum allowable nonlinearity for the power amplifier. This nonlinear behavior of the system is most efficient and quantifiable using ACPR, which can be used to show quite accurately the linearity of a system. In addition to this, new systems employing complex modulation schemes like OFDM impose strict requirements for signal linearity. Therefore, signal linearity is becoming an increasingly important factor in determining how well a wireless system will work, whether it is a cellular network, WLAN network, etc. Indeed, the power amplifier is the main source of the nonlinearities in the system [1-4].

The LInear amplification using Nonlinear Component (LINC) power amplifier is intended for wireless systems since it offers high efficiency with good linearity [5, 6]. However, the output signal may be distorted by imbalance between the two radio frequency (RF) amplifier branches, especially for M-QAM signals [7].

In the literature, one can find several approaches for improving the power amplifier (PA) efficiency while keeping an acceptable linearity. Helaoui et al. [1] introduced the use of a digital signal processing (DSP) algorithm and field programmable gate array (FPGA) implementation in a system, so as to optimize the performance of 3G amplifiers. The study of linearity improvement and efficiency boosting for parallel amplifiers was introduced by Sung et al. [2]. Park et al. [3] suggested a study for the required amplifier back-off for a specified ACPR for OFDM WLAN systems. This work discussed the relationship between the ACPR and the phase nonlinearity of the PA. Kuo et al. [4] presented a study of the ACPR behavior under low pass and band pass power amplifiers. The work in references [2] and [4] introduced a system implementation showing results of the ACPR values without proposing a technique to improve it.

This paper proposes a DSP system solution to improve the linearity of the transmitted signal of wireless transmitter, using filtering of the two LINC branch signals. Also, the effect of different filter types on the resulting transmitted signal is studied. The evaluation of the transmitter output signal quality enhancement by the filtering process can be demonstrated using two metrics, the ACPR and the error vector magnitude (EVM). The ACPR is used to measure the out-of-band emission level caused by the nonlinearity, while the EVM quantifies the in-band distortion effects.

Results of our proposed DSP system solution show a very significant improvement in ACPR performance, which can even help tolerate higher channel interference levels, and LINC imbalance effects. The ACPR improved by 43dB when using a least square filter, allowing for more space to tolerate for channel effects and to protect the system against LINC branch imbalances.

This paper is structured as follows: Section II is a description of the LINC principle, and the modified LINC; and, Section III presents results and performance evaluations of the different filter types employed. Section IV shows results when imbalance is introduced; and finally, conclusions are presented in Section V.

II. LINC Transceiver Architecture

A. LINC Scheme

The conventional LINC amplifier consists of a signal component separation block (SCS), two identical power amplifiers and a combiner. The function of the SCS is to divide the baseband signal into two constant amplitude, phase modulated signals. The two signals are upconverted to the intended carrier frequency, amplified and then summed by the power combiner, so as to reconstruct an amplified undistorted replica of the baseband signal, as shown in Fig. 1. In this manner, the RF power amplifiers are operated at saturation, and the two branch signals yield maximum amplifier efficiency and high linearity as the envelope of both signals is constant in magnitude [5].

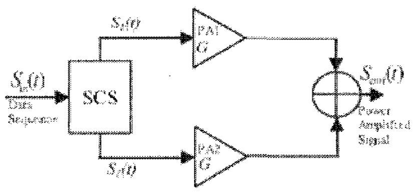

Fig. 1. Regular LINC amplifier architecture

In order to apply the two-branch amplification (LINC technique) to a baseband modulated signal, like the OFDM signal, then $S(t)$ can be decomposed to:

$$s_1(t) = s(t)/2 + e(t) \quad (1)$$

$$s_2(t) = s(t)/2 - e(t) \quad (2)$$

$$e(t) = \frac{j}{2} s(t) \sqrt{s_M^2 / |S(t)|^2 - 1} \quad (3)$$

where S_M is the input signal envelope at saturation. The signal sent is assumed to be a replica of the OFDM signal, $S_{out}(t)$:

$$s_{out}(t) = G\{s_1(t) + s_2(t)\} \quad (4)$$

where G is the complex gain, which may be different for the two branches in the case of an imbalance between the two amplifiers or any other analog components imbalance. The power efficiency of the LINC transmitter can be computed using the following formula:

$$\eta = \eta_a \eta_b \eta_c \quad (5)$$

where η_a is the amplifier efficiency; η_b is the ratio between the average transmitted power and the intended peak power at the transmitter output, which corresponds to the efficiency of the signal recombining process; and, η_c is the combiner efficiency [6].

B. LINC Architecture with Filtered Signals

In this modified LINC architecture, the branch signals are filtered first, after decomposition and before being upconverted. The RF branch signals are then amplified and combined as depicted in Fig. 2. The transmitter contains a DSP block, and a TX RF front end. The DSP block contains the SCS and shaping filters to help lower out-of-band emissions and improve the ACPR value, while at the same time improving the resulting combined signal ACPR. Meanwhile, the power efficiency is maintained, and the value of EVM is kept within the standard limits.

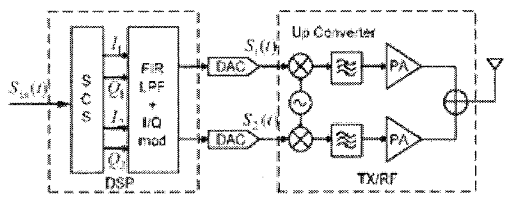

Fig. 2. A new LINC transmitter including FIR LPF block

Results show that this modified architecture has superior performance when compared to the regular amplifier-based transmitter system where the branch imbalance could be tolerated up to a certain limit. The SCS decomposes the baseband signal, $S_{in}(t)$, into the two constant amplitude signals, $S_1(t)$ and $S_2(t)$, and calculates their rectangular representation (I_1, Q_1, I_2, Q_2), respectively. Meanwhile, digital filters are used to filter these signals. Filtering the branch signals of the LINC architecture introduces dynamics in the signal (the peak-to-average power ratio increases from 0.0dB to approximately 3.0dB), forcing the use of linearization of the amplifiers, as they are working near saturation. The resulting IF signals are then converted to analog using digital-to-analog converters (DACs). In the RF front end, the IF signals are upconverted, amplified, combined and then fed to the input port of the transmission antennas.

III. ACPR Reduction Results

To evaluate the performance of the modified system in a practical manner, an indoor Raleigh fading multipath channel was used. In addition, the added white noise (Additive White Gaussian Noise – AWGN) effects were considered. The test signal employed was an IEEE 802.11g OFDM signal with a 2.4 GHz frequency, 20 MHz bandwidth, 64 QAM modulation, 54 Mbps data rate, and signal power of -10.0 dBm. Furthermore, the LINC was constructed using two class AB amplifiers (HMC 408 from Hittite Inc). The amplifiers in the LINC were linearized using the digital predistortion (DPD) technique. The characterizing data for the amplifiers, (AM-AM, AM-PM, and the synthesized AM-AM and AM-PM of DPD) were measured for use in this work. It was assumed that attenuation in the two LINC paths could be neglected. Meanwhile, the filters used were digital FIR lowpass filters, with an order of 60.

The four types of filters studied were least square, equiripple, raises cosine, and window (Kaiser). The pass band frequency for the least square and equiripple filters was 9.5 MHz, and the stop frequency was 10 Mhz; while the cut-off frequency for the raises cosine and window (Kaiser) filters was 9.25 Mhz and 9.5 Mhz, respectively. The filter synthesis was performed using MATLAB. The simulations were carried out using Advanced Design System (ADS) software by Agilent Technologies.

Results for regular LINC amplifier are shown in Fig. 3. The input, output and branch signals spectrum, with respect to the RF carrier frequency of 2.4GHz, show that the ACPR complied with the transmission mask. In addition, from Table I, the efficiency was about 4.72, while the EVM was 1.4%.

The results for the modified LINC (when using the branch filters) for the transmitted signals are shown in Fig. 4. From the figure, one can recognize that the ACPR had improved significantly, especially when the least square filter was used. The use of the least square filter gave a sharp stable spectrum; and, the ACPR was improved by 43dB, and by 36.9dB when compared to the standard specification and the regular LINC amplifier. In addition to this, the EVM was almost not affected, and the efficiency did not change appreciably (from 4.72% to 4.62%). This result implies that the system can tolerate higher channel interference levels and can also self-compensate for LINC imbalances, as demonstrated in the next section. The efficiency when using the equiripple filter was not affected, but at the same time, the EVM was increased by almost 25%, with respect to the regular LINC, due to the ripples in the pass band (0.1dB).

IV. Imbalance Effects Compensation

In this part of the work, branch complex signal imbalance effects between the two LINC branches were studied. It should be noted that the parallel RF branches of the LINC transmitter suffer from a certain amount of unavoidable difference in their magnitudes and phases [7]. The effect of this imbalance was corrected using different techniques that are complex implementations; while the proposed modified LINC using the branch digital filtering offers a solution with no more overhead on the system. The filters improve the ACPR performance of the system and help it to tolerate the imbalance effect.

The least square filter was used. The imbalance values between the two branch signals' magnitudes and phases are shown in Table II: the entries in the table show the EVM values. The ACPR did not change significantly: it was lowered by only 1.3dB in the case when a 3-degree phase and 0.1 magnitude imbalance was considered. In addition, the efficiency was lowered to 4.22%. Of course, cases where the EVM exceeded 5.6% were not accepted as they were over the standard limit.

V. Conclusion

This work proposes a new RF power amplifier architecture, suitable for WLAN IEEE 802.11g applications, based on a DSP implementation of the signal separation process and filtering. The new architecture is based on a modified LINC amplifier in which the signals in the two LINC branches are filtered to lower their ACPR value. The ACPR performance is greatly lowered, which enables the toleration of higher channel interference levels and LINC branch imbalances.

Results show that the ACPR is improved by 43dB when using a least square filter, which allows for more tolerance of channel effects and protection for the system against LINC branch imbalances Meanwhile, the filter action does not affect the system performance in regard to the EVM and the overall power efficiency, as the EVM was almost around that of the case of regular LINC (1.4%) and far less than that of the standard (5.62%).

Table I. The value of ACPR efficiency and EVM, without and with filtering.

Filter Type	*11MHz*	*20MHz*	*28MHz*	Efficin.	EVM
Specs	-20 dBc	-28 dBc	-40 dBc		5.62%
No Filter	-26.1dBc	-51.1 dBc	-56.9 dBc	4.72%	1.40%
Least Sq	-63.8dBc	-66.4dBc	-66.3dBc	4.62%	1.41%
Eq Ripple	-45.8dBc	-63dBc	-63.9dBc	4.71%	1.75%
Raise Cos	-52.2dBc	-59.1dBc	-59.5dBc	4.60%	1.88%
Win-Kaiser	-48.9dBc	-61.9dBc	-60.7dBc	4.64%	1.68%

Table II. The value of EVM for different phase and magnitude imbalances.

Phase/Mag	*0.1*	*0.2*	*0.4*	0.5
1^0	2.26%	3.35%	4.5%	5.15%
2^0	3.12%	3.88%	5.13%	5.9%
3^0	5.05%	5.34%	6.35%	6.62%

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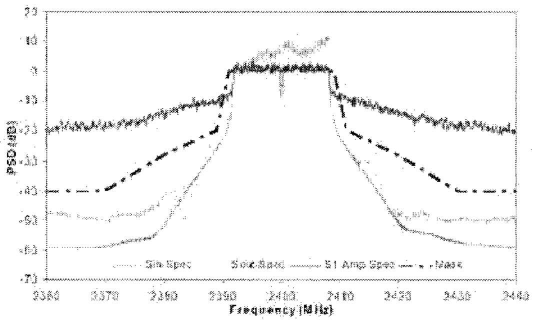

Fig. 3. Branch, transmitted and output signal spectrum using for regular LINC

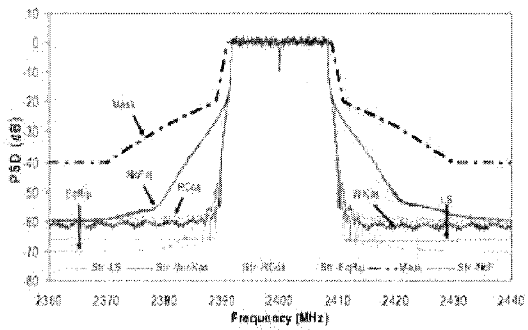

Fig. 4. Transmitted signal spectrum with respect to the mask for modified LINC (using different filters)

Paper 5: ACPR Performance Study for Modified LINC Amplifier

ACPR PERFORMANCE STUDY FOR MODIFIED LINC AMPLIFIER

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Abstract—**A study for the adjacent channel power ratio (ACPR) for modified linear amplification using nonlinear component (LINC) power amplifiers used in wireless communication systems when branch signals are digitally baseband filtered is proposed. The LINC is modified by sending the filtered branch signals and then combine them at the receiver. The IEEE802.11g standard, which operates at 2.4 GHz, employing the OFDM signals is used to show the system performance compatibility with the standard and efficiency improvements. Results show that the ACPR is lowered when using a least square filter, from -26.1dBc to -63.8dBc. The efficiency is improved by 3.4 times when compared with that of a regular LINC.**

I. INTRODUCTION

The wireless communication systems are using digital modulation schemes to acquire maximum benefit from the scarce and crowded spectrum, also to be more efficient with respect to power consumption. In order to meet these restrictions and make use of the available spectrum it is required to take care of the emissions caused by the transmitted signal in the adjacent channels. As the bigger the signal emissions in the adjacent channel bandwidth, the greater the deformation in the adjacent users' channel. In wireless systems, this result in a reduction in the number of active users who can be operating at the same time and also distortions resulting in an increase of the Bit Error Rate (BER), given the accumulation of noise introduced into other users' channels.

Therefore signal linearity is becoming an increasingly important factor in determining how well a wireless system will work, whether it is a cellular network, WLAN network, etc. Indeed, the power amplifier is the main source of the nonlinearities in the system [1-4]. This nonlinear behavior of the system is most efficient and quantifiable using ACPR, which can be used to show quite accurately the linearity of a system. Therefore, the ACPR is one of the most important specifications in wireless transmission, which measures the amount of nonlinear distortions caused by the transmitted signal, and the linearity figure of merit for the power amplifier. New systems employing complex modulation schemes like OFDM impose strict requirements on transmitted signal linearity. The ACPR and the modulation scheme determine the margin of the allowable nonlinearity for the power amplifier.

In the literature, one can find several approaches for improving the power amplifier (PA) efficiency while keeping an acceptable linearity. One of which is the LINC power amplifier that is intended to be used in wireless systems since it offers high efficiency with good linearity [5, 6]. However, due to some problems in circuitry such as component mismatch between the two branches, like the imbalance due to the mismatch among the two radio frequency (RF) amplifiers. Which causes the output signal to be distorted especially for M-QAM signals [7] causing final signal degradation. LINC also suffers from power efficiency degradation due to the signal RF combiner used to reconstruct the signal after the amplification stage. As the average efficiency of LINC amplifier depends on the signal dynamics and the combiner's efficiency [8, 9]. The two types of combiners commonly utilized are the matched power combiner and the Chireix outphasing combiner. The matched combiner, comprised by two-way isolated power combiner results in an excellent linearity, but degrades the overall power efficiency of the LINC system. The Chireix outphasing combiner is described as a lossless combiner that improves the power efficiency, but degrades the linearity which is not suitable for wireless communication systems.

This paper proposes a DSP system level solution that is intended to improve the linearity of the transmitted signal of wireless transmitter. By modifying the regular LINC architecture, through baseband digital filtering of the LINC branch signals, then transmitting them, and perform signal combination at the receiver to overcome the combining problems of the regular LINC systems. Also, in this paper, the effect of different filter types on the resulting transmitted signal is studied. The evaluation of the transmitter output signal quality by the filtering process is demonstrated using two metrics, the ACPR and the error vector magnitude (EVM). The ACPR is used to measure the out-of-band emission level caused by the nonlinearity, while the EVM quantifies the in-band distortion effects. The back-off operation point, average transmitter overall efficiency, the peak to average power ratio (PAPR) are computed to evaluate the proposed transceiver efficiency in comparison to that of a regular LINC transceiver too.

Results of the proposed system show an improvement in ACPR performance, that can help the system tolerate higher channel interference levels, and the LINC imbalance effects. The ACPR improved by 43dB when using a least square filter, allowing for more space to tolerate for channel effects and to protect the system against LINC branch imbalances. In addition to this the system efficiency was augmented by almost 3.4 times when compared to that of a regular LINC, since the combiner component burden is eliminated.

This paper is structured as follows: Section II presents a description of the LINC principle, and introduces the

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modified LINC; Section III presents results for the ACPR performance. Section IV shows results of ACPR performance when different filter types used. Finally, conclusions are presented in Section V.

II. LINC Architecture

A. Regular LINC

A regular LINC amplifier consists of a signal component separation block (SCS), two identical power amplifiers and a combiner. The function of the SCS is to divide the baseband signal into two constant amplitude, phase modulated signals. The two signals are upconverted to the intended carrier frequency, amplified and then summed by the power combiner, so as to reconstruct an amplified undistorted replica of the baseband signal, as shown in Fig. 1. In this manner, the RF power amplifiers are operated at saturation, and the two branch signals yield maximum amplifier efficiency and high linearity as the envelope of both signals is constant in magnitude [5].

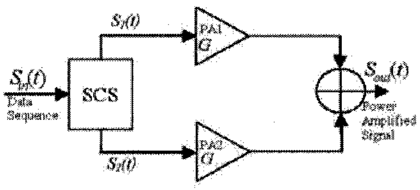

Fig. 1. Regular LINC amplifier architecture

In order to apply the two-branch amplification (LINC technique) to a baseband modulated signal, like the OFDM signal, then $S(t)$ can be decomposed to:

$$s_1(t) = s(t)/2 + e(t) \tag{1}$$

$$s_2(t) = s(t)/2 - e(t) \tag{2}$$

$$e(t) = \frac{j}{2}s(t)\sqrt{s_M^2 / |S(t)|^2 - 1} \tag{3}$$

where S_M is the input signal envelope at saturation. The signal sent is assumed to be a replica of the OFDM signal, $S_{out}(t)$:

$$s_{out}(t) = G\{s_1(t) + s_2(t)\} \tag{4}$$

where G is the complex gain, which may be different for the two branches in the case of an imbalance between the two amplifiers or any other analog components imbalance. The power efficiency of the LINC transmitter can be computed using the following formula:

$$\eta = \eta_a \eta_b \eta_c \tag{5}$$

where η_a is the amplifier efficiency; η_b is the ratio between the average transmitted power and the intended peak power at the transmitter output, which corresponds to the efficiency of the signal recombining process; and, η_c is the combiner efficiency [6].

B. Proposed Modified LINC

In regular LINC amplifier the branch signals are being combined before transmission. While in the modified LINC architecture, the amplified branch signals are transmitted directly after being filtered to fit the standard mask, and amplified. The signal combination takes place at the receiver side, by the receiver antennas as shown in Fig. 2. The transmitter contains a DSP block, and a TX RF front end. The DSP block contains the SCS and shaping filters. The SCS decomposes the baseband signal, $S_m(t)$, into the two constant amplitude signals, $S_1(t)$ and $S_2(t)$, and calculates their rectangular representation (I_1, Q_1, I_2, Q_2), respectively. The digital shaping filters are used to fit the signal in each branch within the standard mask, and help lower out-of-band emissions, thus the ACPR of the resulting system is improved. Filtering the branch signals of the LINC architecture introduces dynamics in the signal (the PAPR increases from 0.0dB to approximately 3.6dB), forcing the use of linearization of the amplifiers, as they are working near saturation.

The receiver has a standard structure; it contains an RF front end, which consists of RX receiver, RF/IF conversion stage, A/D converter and a digital DSP block. The DSP block is used to process the received signal to overcome the transmitter masking effect and the channel effects. In this manner the power efficiency is improved, while the LINC branch imbalance effects could be tolerated up to some extent, and also can be treated using the technique introduced in [7]. The values of the EVM, PAPR for this modified architecture assuming an ideal channel is 0.39% and 3.66dB respectively. These results show superior performance when compared to the regular LINC, and regular single branch amplifier.

III. System ACPR Performance

The performance of the proposed modified LINC system is to be evaluated using an indoor Raleigh fading multipath channel, in addition white noise, additive white Gaussian noise (AWGN) effects were considered. An IEEE 802.11g OFDM signal with a 2.4 GHz frequency, 20 MHz bandwidth, 64 QAM modulation, 54 Mbps data rate, and signal power of -10.0 dBm was employed as the test signal. Two class AB amplifiers (HMC 408 from Hittite Inc) were utilized to construct the LINC. The digital predistortion (DPD) technique was used to linearize the amplifiers in the LINC to overcome the filter effect (increasing the PAPR). The LINC amplifiers characterizing data, (AM-AM, AM-PM, and the synthesized AM-AM and AM-PM of DPD) were measured to be used in this study. The attenuation in the two LINC paths was assumed to be neglected.

Meanwhile, the filters used were digital FIR lowpass filters, with an order of 60. The MATLAB software was used for filter synthesis. The Advanced Design System (ADS) software by Agilent Technologies was used to perform the simulations.

The efficiency was about 4.72% for regular LINC amplifier while the EVM was 1.4% as shown in Table I. When applying the filtering action in the modified LINC system, and transmitting the branch signals, it was found that the efficiency is enhanced by about 3.4 times, and the EVM is still almost the same. Fig.4 shows the spectrum of the transmitted branch signal of the modified LINC compared to the spectrum of the transmitted signal of a regular LINC, both with an adjacent channel of a regular single branch amplifier. It can be seen that the branch signal of the modified LINC is complying with the standard mask; meanwhile the ACPR performance of the system is not deteriorated. In addition the system efficiency is improved, as shown in table I, if the regular LINC results are compared with those of the modified LINC when a least square filter is used.

IV. Filter Type Effect on ACPR

The four types of filters studied were least square, equiripple, raised cosine, and window (Kaiser). The pass band frequency for the least square and equiripple filters was 9.5 MHz, and the stop frequency was 10 MHz; while the cut-off frequency for the raises cosine and window (Kaiser) filters was 9.25 MHz and 9.5 MHz, respectively.

The modified LINC ACPR performance results (when using different branch filters) are shown in Fig. 3. It can be noted from the figure, that the ACPR had improved significantly, especially when the least square filter was used. The use of the least square filter results in a sharp stable spectrum; and the ACPR was improved by 43dB, and by 37dB when compared to the standard specification and the regular LINC amplifier respectively. In addition, the EVM was almost not affected; meanwhile the efficiency was improved almost by 3.4 times than that of regular LINC (from 4.72% to 16.17%). This result implies that the system can tolerate higher channel interference levels and can also self-compensate for LINC imbalances. The efficiency when using the equiripple filter was not affected, but at the same time, the EVM was increased by almost 25%, with respect to the regular LINC, due to the ripples in the pass band (0.1dB).

The parallel RF branches of the LINC transmitter suffer from a certain amount of unavoidable difference in their magnitudes and phases [7]. The effect of this imbalance was corrected using different techniques that are complex implementations; while the proposed modified LINC using the branch digital filtering offers a compensation with no more overhead on the system. The filters improve the ACPR performance of the system and help it to tolerate the imbalance effect.

V. Conclusion

This work is proposing a new RF power amplifier architecture based on a modified LINC suitable for WLAN IEEE 802.11g applications, based on a DSP implementation of the signal separation process, branch signal filtering, and signal combining at the receiver side. In this system the signals in the two LINC branches are filtered to fit the transmission mask and lower their ACPR. The ACPR performance is greatly lowered, which enables the toleration of higher channel interference levels and LINC branch imbalances. Mean while the system overall efficiency is improved as the combiner in the transmitter is removed.

Results show that the ACPR is improved by 43dB when using a least square filter, which allows for more tolerance of channel effects and protection for the system against LINC branch imbalances. Meanwhile, efficiency is enhanced by 3.4 times when compared to that of a regular LINC amplifier. The filter action does not affect the system performance in regard to the EVM, as the EVM was almost around that of the case of regular LINC (1.4%) and far less than that of the standard (5.62%).

Table I. The value of ACPR efficiency and EVM, without and with filtering.

Filter Type	*11MHz*	*20MHz*	*28MHz*	Efficiency	EVM
Specs	-20 dBc	-28 dBc	-40 dBc		5.62%
No Filter	-10.5dBc	-14.7 dBc	-16.0 dBc		1.50%
Reg. LINC	-26.1dBc	-51.1dBc	-56.9dBc	4.72%	1.40%
Least Sq.	-63.1dBc	-70.2dBc	-70.2dBc	16.17%	1.53%
Eq. Ripple	-42.8dBc	-42.2dBc	-44.5dBc	16.17%	1.84%
Raised Cos	-40.4dBc	-58.1dBc	-62.0dBc	16.27%	1.97%
Win-Kaiser	-36.0dBc	-52.5dBc	-58.7dBc	16.30%	1.78%

VI. References

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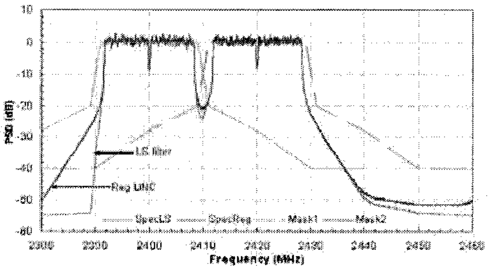

Fig. 3. Transmitted signal spectrum with respect to the mask for modified LINC (LS least square filter) and regular LINC with adjacent channel

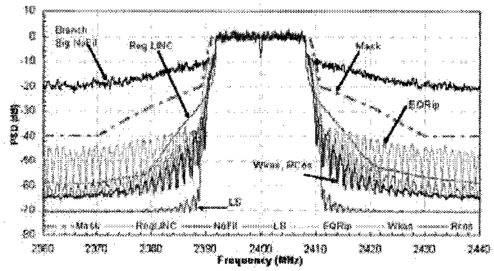

Fig. 4. Transmitted branch signal spectrum with respect to the mask for modified LINC (using different filters LS least square, WKAS window Kaiser, EQRip Equiripple, RCos Raised Cosine)

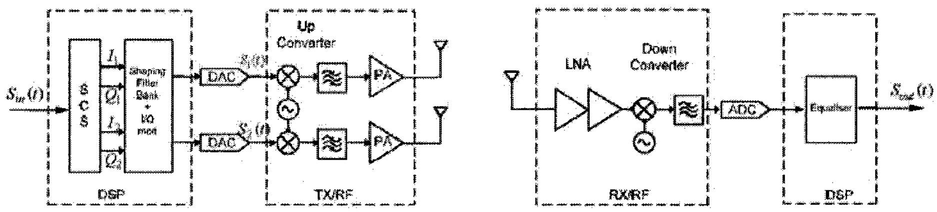

Fig. 2: Detailed layout of the proposed Modified LINC architecture.

Appendix C: ADS Simulations and Schematic of a LINC Amplifier:

The simulations were carried out using the software Advanced Design System (ADS), from Agilent technologies. This software is an Electronic design automation software platform offering complete design integration for products such as cellular and portable phones, wireless networks, radar and satellite communications systems. Agilent EEsof EDA is the leading supplier of Electronic Design Automation (EDA) software for high-frequency system, circuit, and modeling applications. Electronic System-Level (ESL) design tools from Agilent EEsof EDA enable designers of high-performance PHY's in emerging wireless communications systems, satellite and radar systems, and software-defined radio to make optimum use of the latest RF/Analog and Digital Signal Processing techniques. It is used by system designers to deliver physical layer architectures in less time with higher system throughput and less wasted design margins.

The simulations were carried out for the WLAN 802.11a_Tx_prj.

In these simulations it is assumed that:

Different system components like the combiner were assumed to be ideal.

No imbalance between the two paths of the LINC.

The channel models used are:

A) Ideal channel, with unitary response.

B) Fading indoor channel, with added white noise.

C-1 Simulation control parameters and signal generation:

The WLAN_80211g_RF source signal was used. The signal generated was an IEEE 802.11g OFDM, the central frequency 2.4 GHz, having bandwidth BW= 20 MHz, the subcarrier modulation was 64QAM, the data rate = 54 Mbps, the input power Pin = -10.0 dBm.

The Data Flow (DF) analysis was used to control all the simulations. The DF controller is used to control the flow of the mixed numeric and timed signals for all digital signal processing simulations within ADS. This controller, together with source and sink components, provide the flexibility to control the duration of simulation.

The different parameters used in the DF are:

Default numeric start = 0.0

Default numeric stop = 10000

Default time start = 0.0 μsec

Default time stop = 352.0 μ sec (time for two OFDM frames).

The RF channel variables were:

IF frequency = 380 MHz

RF frequency = 2400 MHz

RF_BW = 20.0 MHz

The time step = 12.5 nsec.

The measurement of the variables was done for 40 points starting from sample number 30. Figure C-1 shows the different items described above, which are used in the simulation process. At different points in the data flow the signals were measured simultaneously in time domain and frequency domain (power spectrum). Figure C-2 shows the input signal measurement point.

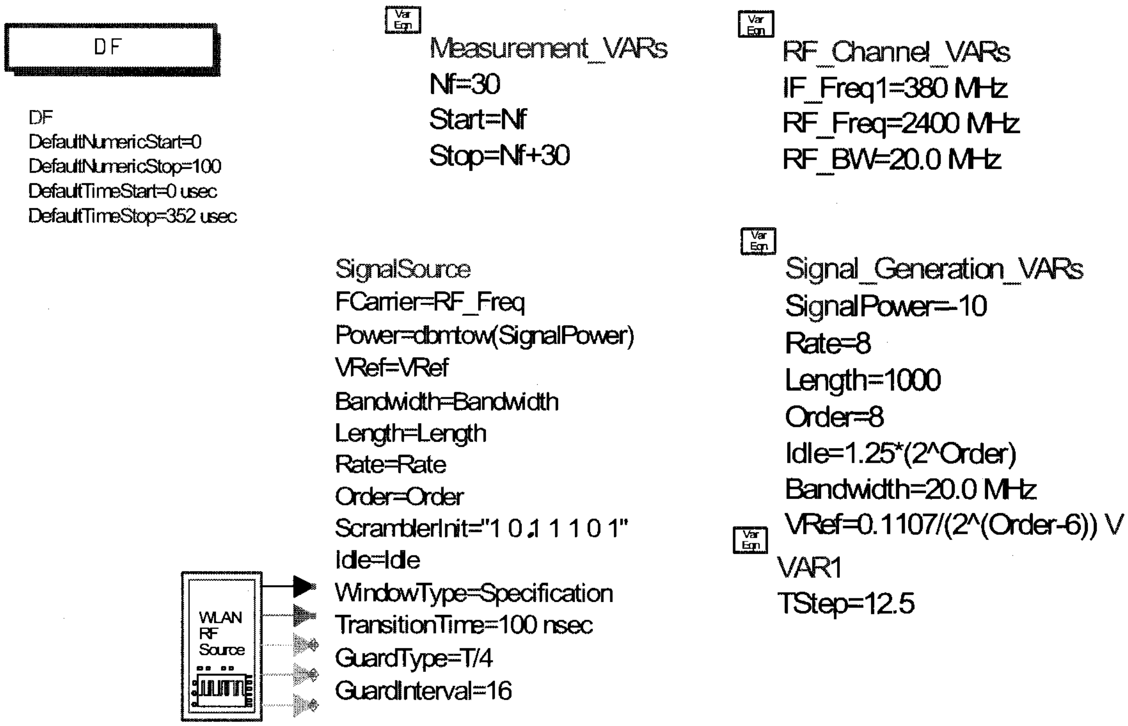

Figure C- 1: Different simulation DF blocks and WLAN signal RF source and variables items described above used in the simulation process.

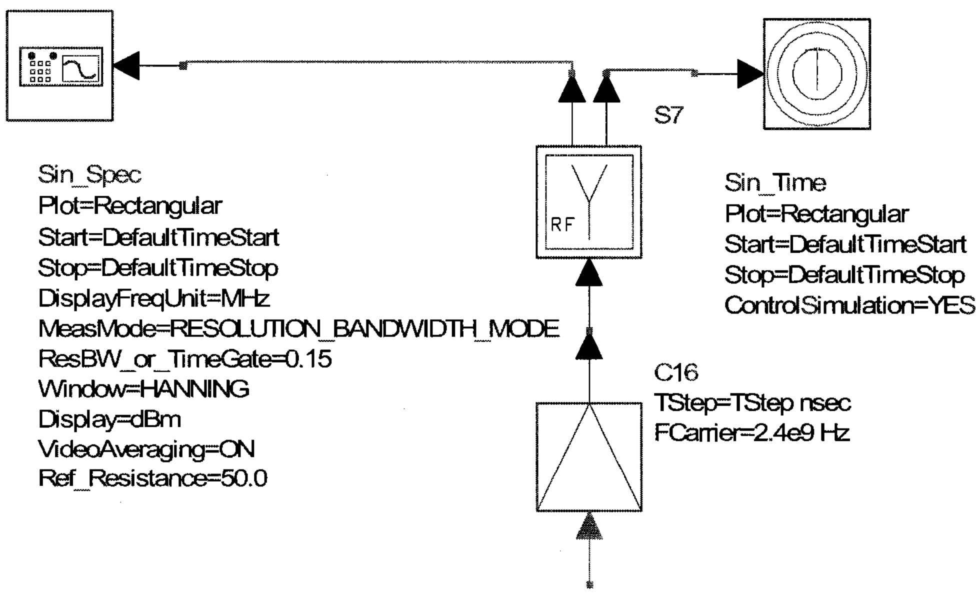

Figure C- 2: Input signal measurement point.

C-2 Signal Decomposition and power amplifier implementation:

The second step was to develop the signal separation process, and was based on first computing the error signal *e(t)*, as shown in Figure C-3. Then the two branch signals are generated by adding and subtracting the error signal to half of the original signal *s(t)* as shown in Figure C-4. The error signal calculation is done in the block called ET in the diagram.

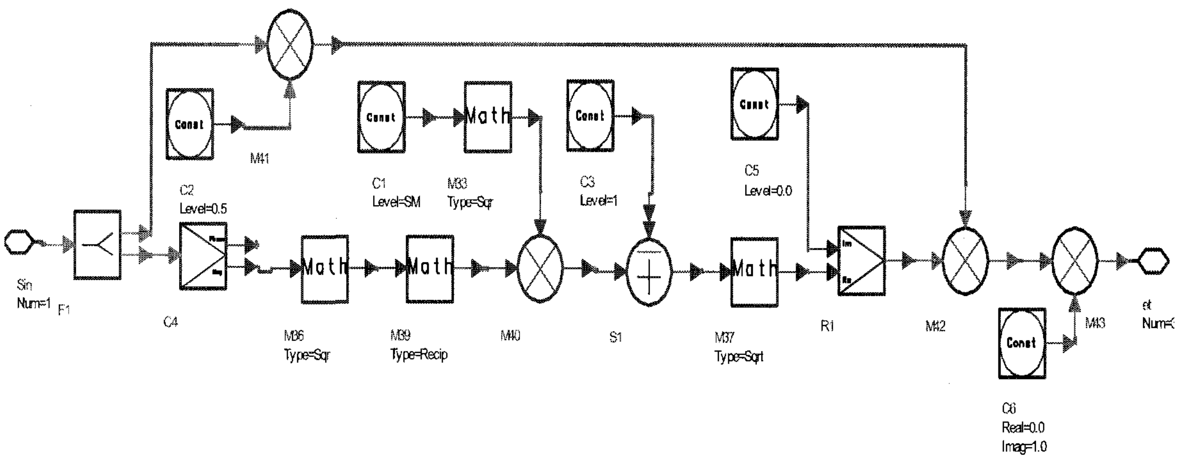

Figure C- 3: The calculation of the error signal in ADS

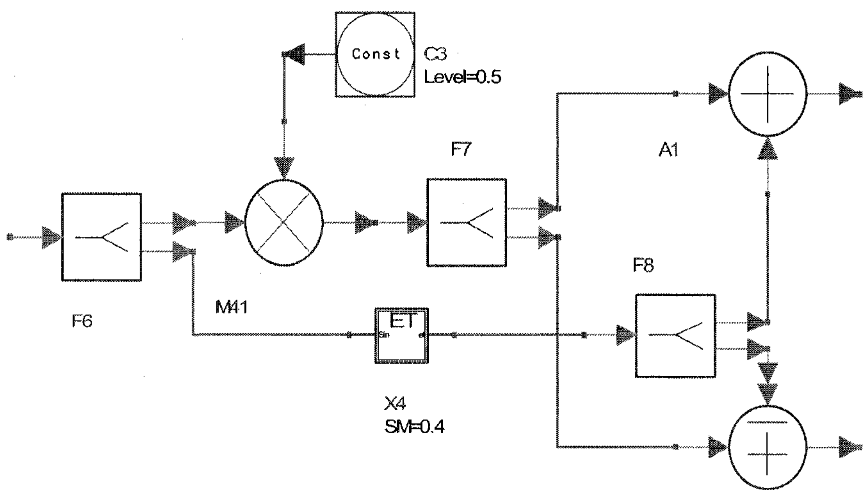

Figure C- 4: Signal decomposition implementation in ADS.

The power amplifiers used were two class AB, HMC 408 from Hittite Inc. The Gain and phase response of the amplifiers with the Digital PreDistorter is shown in Figure C-5. The power amplifier lineup is shown in Figure C-6; also in the same figure the up conversion stage is depicted. While in Figure C-7 the power amplifier with the digital PreDistortion block is demonstrated. In Figure C-8 the ADS block diagram is shown.

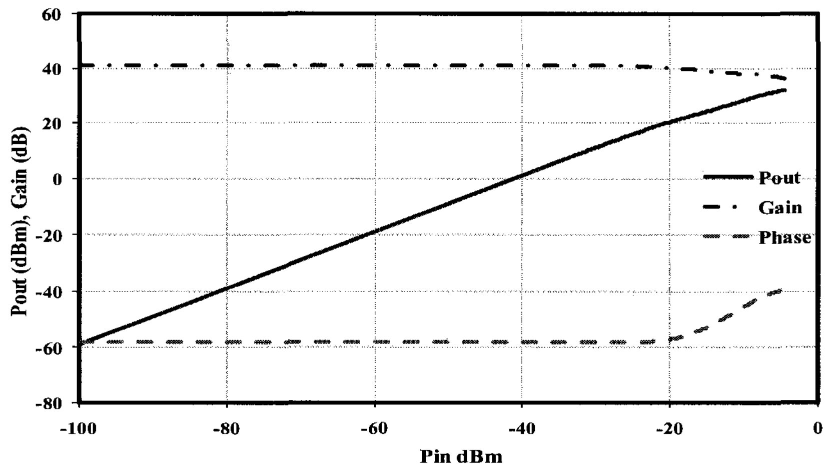

Figure C- 5: The AM-AM, AM-PM characteristics of the used amplifiers.

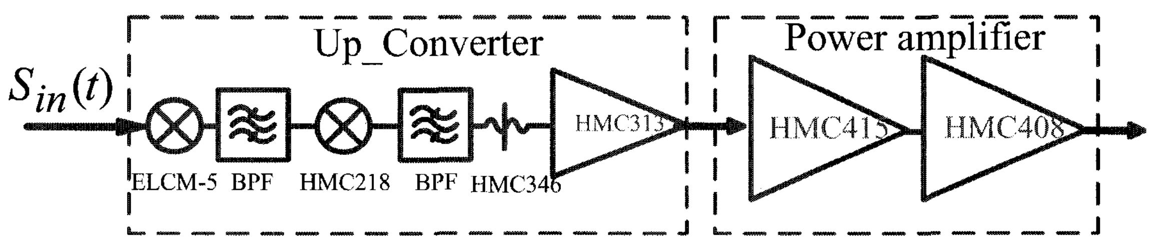

Figure C- 6: The used power amplifier line up showing also the up conversion stage.

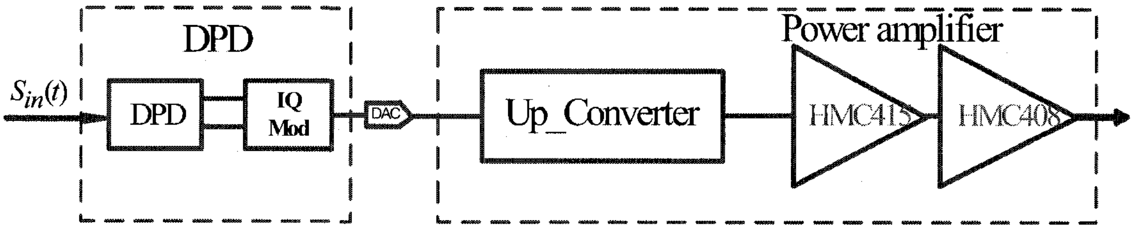

Figure C- 7: The used power amplifier line up, up conversion stage and the Digital PreDistortion block.

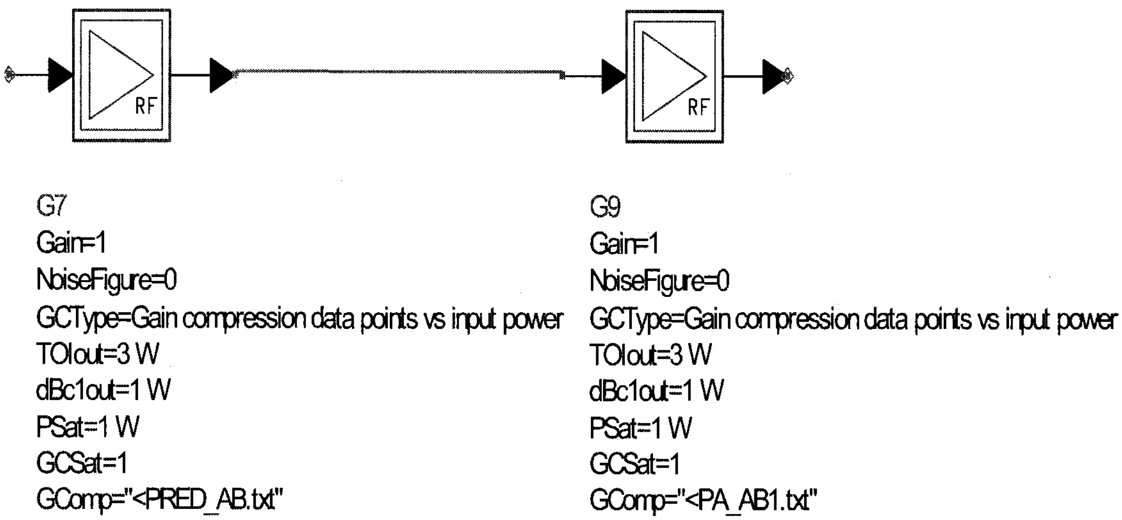

Figure C- 8: The two ADS blocks used to simulate the power amplifier and its DPD block.

C-3 Transmit and receive antenna, channel blocks:

The channel and the added white noise blocks are depicted in Figure C-9. In addition, the transmitter and the receiver antennas are shown in the same figure. The channel used has a multipath fading model, while the transmitting antenna was used at the base station and the receiving antenna at the mobile side.

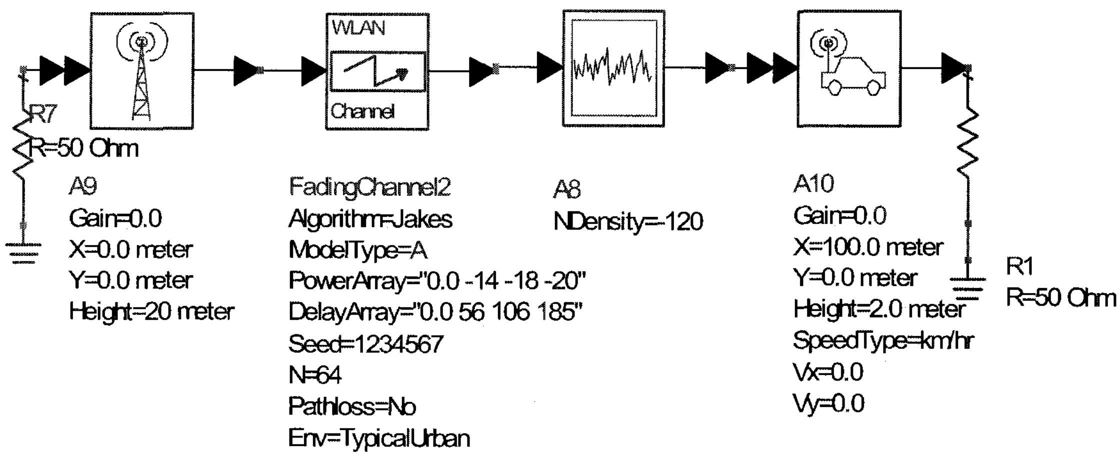

Figure C- 9: The transmitting antenna, multipath fading channel, added white noise and the receiving antenna blocks.

C-4 Filter of the branch signal:

The implementation block for one of the branch signals is shown in Figure C-10. Here the branch signal is divided into the Inphase (*I*), and Quadrature (*Q*) components, and then they are filtered. The filter block input file contains the filter tabs in text format, which are synthesized using MATLAB.

C-5: Regular LINC and Modified LINC in ADS:

The ADS implementation of the regular LINC is depicted in Figure C-12. It should be mentioned here that for the case of the modified 2X1 LINC there will be two transmitting antennas, two channel paths, an RF summer and then a receiver antenna. Figure C-11 is showing the two signal (channel) paths and the RF summer and the receiving antenna. The final stage will be the receiver, and EVM calculations. The Error Vector Magnitude (EVM), block has two inputs, one is the output RF signal, while the other input is a feedback from the WLAN signal source. The EVM block contains a regular WLAN receiver and additional blocks to compute the EVM value.

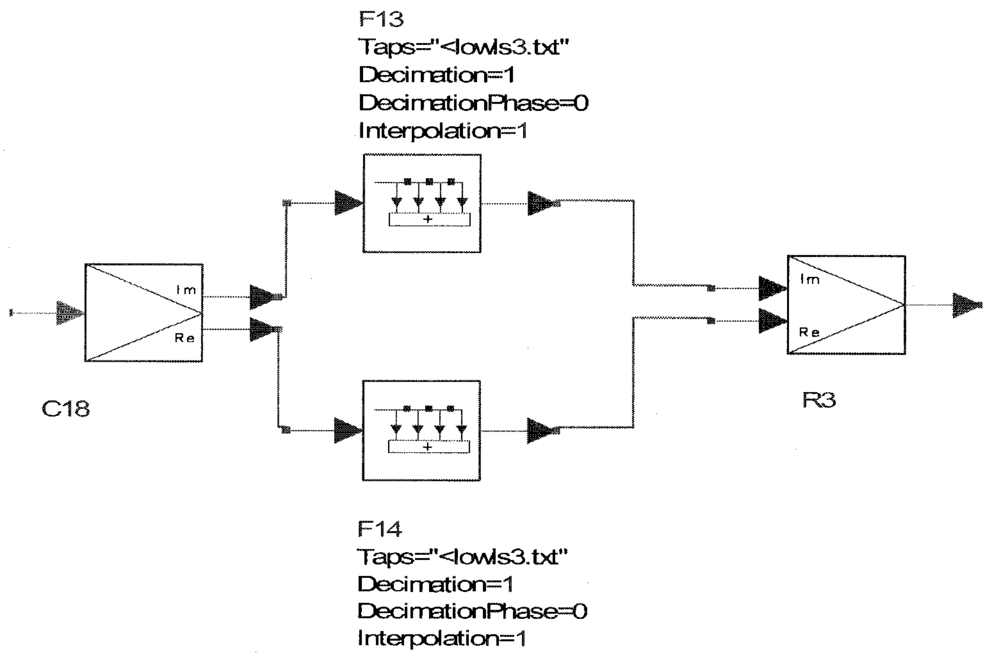

Figure C- 10: The filter bank for one of the branches.

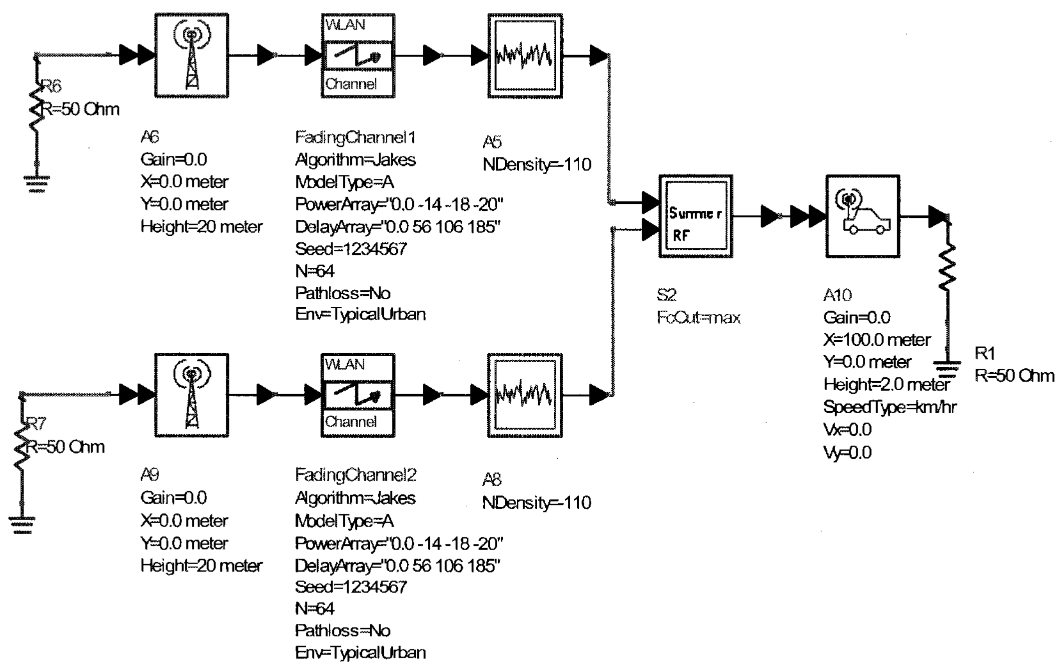

Figure C- 11: The Error Vector Magnitude (EVM) Block

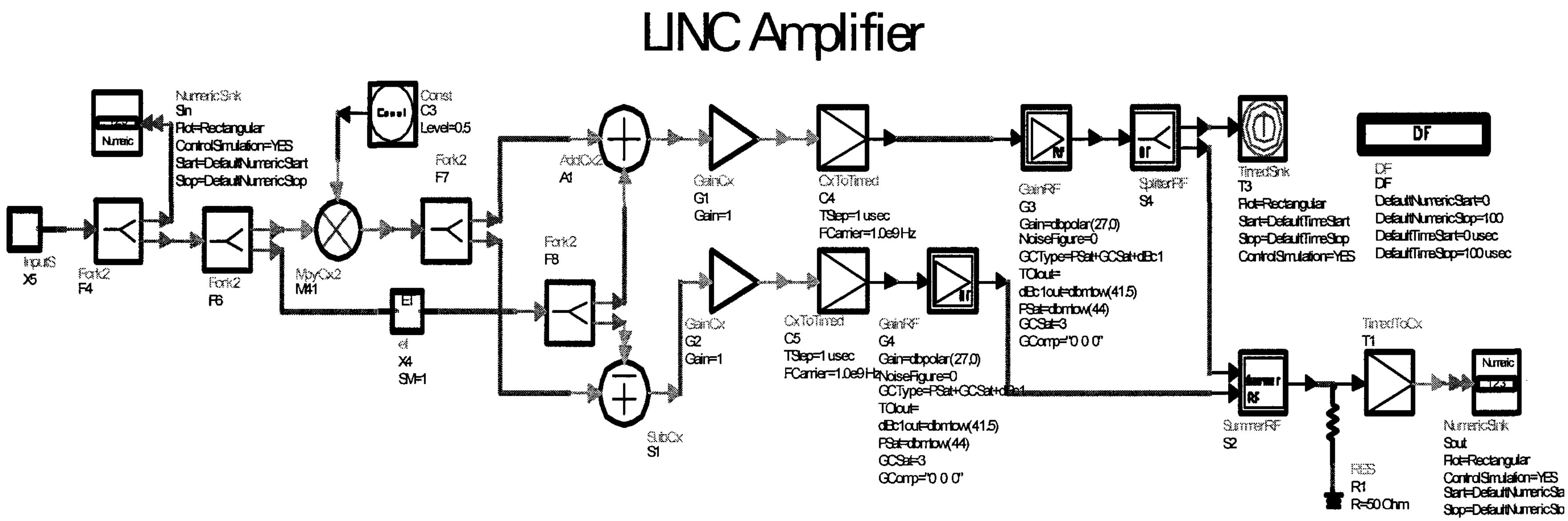

Figure C- 12: ADS implementation of a regular LINC amplifier